MASTER'S THESIS

MASTER'S DEGREE IN ENERGY ENGINEERING

Design and Simulation of a 10MW Grid-Connected PV System

MEMÒRIA

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Abstract

The main goal of this final master thesis is to design and make a comparative analysis of two different solar cell technologies (monocrystalline solar cell and polycrystalline solar cell) in a 10MW grid-connected PV system located in Cabrera de Mar. This comparison was done by analyzing the Levelized Cost of Energy (LCOE) and the payback time of the projects.

The thesis was divided in three main parts. The first part exposes the state of art of the photovoltaic applications showing how the solar energy is converted to electricity, and a summary of the different solar cell technologies. The second part present the legislation requirements in Europe and Spain and fishes with an explanation of the Spanish electric market. The third part present the sizing of the different systems which includes the geographical situation and the meteorological data of the selected location, the component selection and the sizing and simulation of the two PV systems evaluated. In this last part the results obtained are presented showing the requirements and the economic analysis of each PV system.

The simulation has been done by using the software PVSYST, which have a wide database of the components and meteorological parameters required for the PV systems simulation.

After analyzing the results obtained for the different PV systems is possible to determine which photovoltaic technology is preferable. The results show that polycrystalline PV system is more cost effective, because the LCOE or in other words the cost per kWh produced is lower than the cost obtained for the monocrystalline PV and in addition the investment payback is produced in less time.

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1. Introduction

The climate change is one of the most important challenges of our time. In 2013 was published the fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC) [24]. The report shows the result of a calculation for the maximum future CO_2 emissions in order to restrict the global warming to less than 2ºC. In 2012 half of those emissions were achieved, also the average global temperature had increased 0,85ºC between 1880 and 2012, and the ocean level has raised 19 cm in the last century. All these changes will produce catastrophic consequences in the entire world, making necessary the application of all the measures that we can in order to try to reduce them.

In addition, the volatility and the increasing costs of the fossil fuels are generating a necessity in the governments of reducing its energy dependence.

In order to achieve the goal of reducing the utilization of fossil fuels, which can help the fight against the global warming and the reduction of the fossil fuel dependence, a rising awareness with sustainability is being produced in many countries. Since 2006, the renewable energy capacity has increased to around 2.179.099 MW in 2017 [25], which represents an increase of a 106% showing a clear change towards a renewable energy future.

In this framework the European Union have fixed in the Directive 2018/2001, about the promotion of the use of energy from renewable sources, the binding objective of increasing the share of energy from renewable sources in the gross final consumption to a 32% in 2030 [26]. In 2017 the percentage of renewable energy consumption stood at 17,5% in path to the 2020 target of 20% set in 2007 [27], that shows that is still necessary to continue investing in efficiency and renewable energies to achieve the 2030 target.

These initiatives of the EU fix the specific targets for each country. In 2017 the percentage of gross final consumption from renewable energies in Spain was of a 17,5% [28], at 2,5% from its 2020 target. Focusing in the electric system Spain was sharing a 37% of energy from renewables in 2016 which is close to the target of 38,1% by 2020 [29]. Instead of the fact that Spain is on the way of the energy transition, the country is nowadays really far from the objectives announced by the Spanish government of a 35% of renewable energy consumption in 2030. To achieve this objective Spain will have to install 50MW more of renewable energies for 2030.

The goal of this study is to design a 10MW grid-connected PV power plant using for that the most used PV technologies in plants of this size, monocrystalline and polycrystalline, and then make a comparison between them based on the results.

2. Properties of light

In this chapter is an introduction to the most important properties of light. Most of the concepts exposed in this point have been obtained from the online book PV EDUCATION [6].

The light that we can see is just a fraction of the total energy emitted by the sun, and this energy is composed by many different wavelengths.

As Einstein explained in 1905 light is made up of indistinguishable energy elements or quanta of energy, and it can be treated as a wave as a particle or as a photon. As can be seen in the following equation the energy of a photon has an inverse relation with the wavelength of the light:

$$E = \frac{hc}{\lambda} \qquad \text{(Eq. 1)}$$

Where:
E: Energy of a photon;
h: Planck's constant ($6{,}626 \cdot 10^{-34}$ J/s);
c: Speed of light ($2{,}998 \cdot 10^{8}$ m/s);

This inverse relation between energy and wave length means that light of high energy photons, as blue light, has a short-wave length and red light with a larger wave length has low energy photons.

Normally, in order to characterize the wave length, the most used way is characterizing it by the spectral irradiance as a function of the wavelength, that gives the power density at a particular wavelength ($Wm^{-2}\mu^{-1}$) also for solar cells analysis the photon flux is needed because determines the number of electrons generated.

$$F(\lambda) = \phi E \frac{1}{\Delta\lambda} \qquad \text{(Eq. 2)}$$

$$\phi = \frac{num\ of\ photons}{\sec m^2} \qquad \text{(Eq. 3)}$$

Where:
F is the spectral irradiance ($Wm^{-2}\mu^{-1}$);
ϕ is the photon flux;
E is the energy of the photon (J);
λ: is the wavelength of the photon;

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However, to know the total power emitted from a light source we need to integrate the spectral irradiance over all wavelengths., a closed form equation often does not exist instead we must multiply the measured spectral irradiance by a wavelength range over which is measured and then calculated over all wavelengths.

$$H = \sum_{i} F(\lambda)\Delta\lambda \qquad \text{(Eq. 4)}$$

Where:
H is the total power density in Wm^{-2}
F(λ) is the spectral irradiance in $Wm^{-2}\mu^{-1}$
$\Delta\lambda$ is the wave length

Sun and other light sources are commonly modelled as "blackbody" emitters, a blackbody absorbs all radiation that impacts on it and emits radiation based on its temperature. In photovoltaics the blackbody sources of interest are the ones that emit light in the visible region, and its spectral irradiance is given by Plank's radiation law, shown in the following equation:

$$F(\lambda) = \frac{2\pi hc^2}{\lambda^5 \left(\exp\left(\frac{hc}{k\lambda T}\right) - 1\right)} \qquad \text{(Eq. 5)}$$

Where:
λ is the light wavelength
T is the temperature of the blackbody (K)
F(λ) is the spectral irradiance in $Wm^{-2}\mu^{-1}$
h, c and k are constants

As it has been explained above to know the total power density is necessary to integrate, over all wavelengths, the spectral irradiance of the blackbody which gives:

$$H = \sigma T^4 \qquad \text{(Eq. 6)}$$

Where σ is the Stephan -Boltzmann constant [$5{,}67\cdot10^{-8}$ $Wm^{-2}K^{-4}$] and T is the temperature of the blackbody in kelvin.

According to Plank's law the spectrum of the radiation is determined by T, not by the body shape or composition. Intensity, or instantaneous power radiation received per unit of surface (Wm^{-2}), increases across all wavelength as temperature increases.

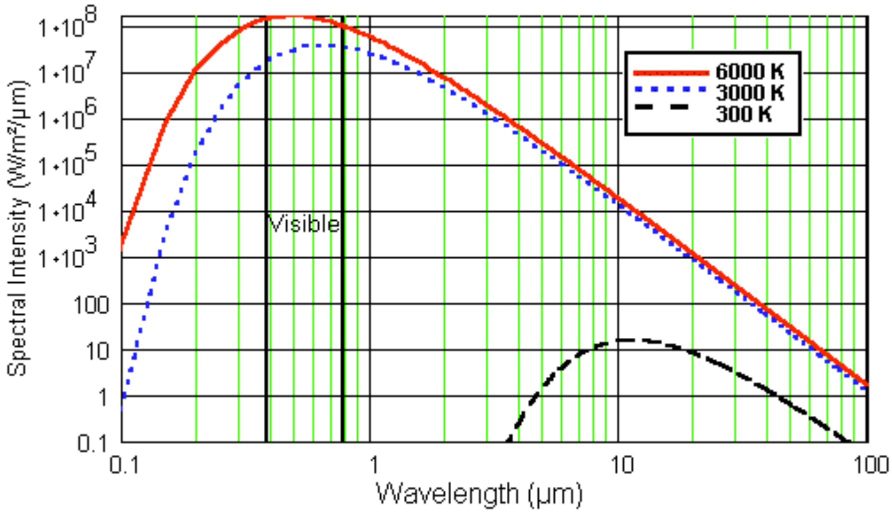


Fig. 2-1: Radiation distributions for perfect blackbodies [6].

Wien's law is used to know the wavelength peak where the spectral irradiance is higher or most of the power is emitted.

$$\lambda_p = \frac{2900}{T} \qquad \text{(Eq. 7)}$$

Where λ_p in µm is the wavelength where the peak spectral irradiance is emitted and T is the blackbody temperature.

3. Solar radiation

The following chapter is a summary of some parameters related to the solar radiation that, are necessary to consider and understand in the photovoltaic plant sizing. As in the previous chapter these concepts have been obtained from book PV EDUCATION [6].

The photosphere, which is the name used to refer to the surface of the Sun, is at a temperature of about 6000K and it can be considered a blackbody. The calculated solar irradiance at the Earth atmosphere is the solar constant and has a value of 1366 Wm^{-2}.

Instead of the fact that the solar radiation incident at the Earth atmosphere can be considered constant, for photovoltaic applications, at the Earth's surface it varies widely and these variations are caused mostly because of the following points.

3.1. Atmospheric effects

Solar radiation at the Earth surface is hugely influenced by atmospheric effects, for photovoltaic applications the major effects which reduce the power of the solar radiation are absorption, scattering and reflection being the most important the absorption and scattering due to air molecules and dust.

Due to these effects, radiation is separated into three different components: direct and diffuse radiation, and albedo. The first one, also called "beam radiation", is the most important in photovoltaic applications; the diffuse radiation is the one that reaches the Earth after being scattered by molecules or particles and the last one is the direct and diffuse radiation that is reflected on the ground or other close surfaces.

3.2. Air mass

Air mass is the direct path length of the radiation through the atmosphere, and is determined by the position of the Sun in relation with zenith of the place where the power facility is going to be installed.

$$AM = \frac{1}{\cos{(\theta)}} \quad \text{(Eq. 8)}$$

Where θ is the angle from the vertical (zenith angle).

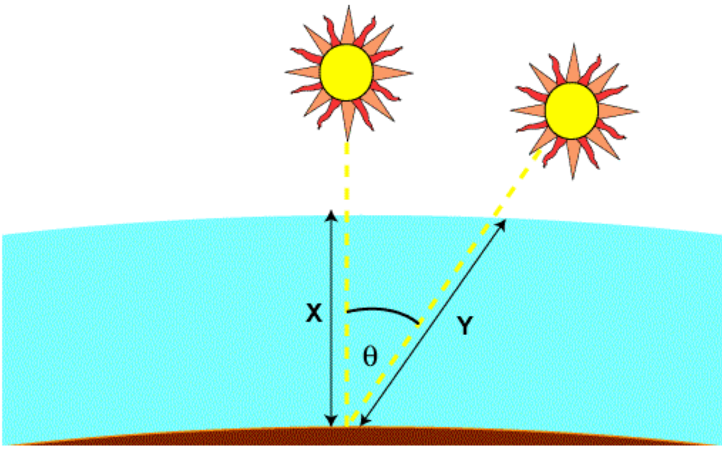


Fig. 3-1: Air mass representation [6]

The standard spectrum outside the Earth atmosphere is called AM0, used to estimate the performance of solar cells in the space. But at the Earth surface the standard spectrum is called AM1.5G which includes direct and diffuse radiation and has been normalized to give $1000Wm^{-2}$.

3.3. The season of the year and the time of the day

The position of the Sun varies with the location at the Earth, the season of the year and the time of the day changing the angle at which the beam radiation impacts the Earth. These variations make necessary to use some Sun angles for PV sizing which are explained below [6].

The declination angle (δ) varies seasonally because of the inclination of the Earth's axis of rotation and the rotation of the Earth around the Sun. This angle changes from 23,45º at the summer solstice to -23,5º at the winter solstice, having a value of 0º during the two equinoxes. It can be calculated by the equation:

$$\delta = -23{,}45^{\circ} \cdot \cos\left(\frac{360}{365} \cdot (d+10)\right) \qquad \text{(Eq. 9)}$$

Being *d* the day of the year (ie: Jan 1 is d=1)

However, the two more important angles in solar photovoltaic applications are the elevation angle and the azimuth angle.

The elevation angle (α) is formed by the angle of the Sun measured from the horizontal, being it 0º at the sunset and at the sunrise. This angle at its maximum, at solar noon, is a very important parameter for solar photovoltaics. It can be calculated by using the following formula:

$$\alpha = \sin^{-1}[sin\delta sin\varphi + cos\delta cos\varphi \cos(HRA)] \quad \text{(Eq. 10)}$$

Where HRA is the hour angle, and converts the local solar time into the number of degrees that the Sun moves across the sky, and φ is the latitude at the location of interest.

The azimuth angle (ψ) is formed between the surface of the module and the exact south direction, and can be calculated by using the following equation:

$$\psi = \cos^{-1}[\frac{sin\delta sin\theta + cos\delta cos\theta \cos(HRA)}{\cos(\alpha)}] \quad \text{(Eq. 11)}$$

3.4. Solar radiation on a tilted surface

The angle of the PV module respect the Sun is very important in order to obtain the maximum power from the module. When it is perpendicular to the sunlight the power density on the module will be at its maximum.

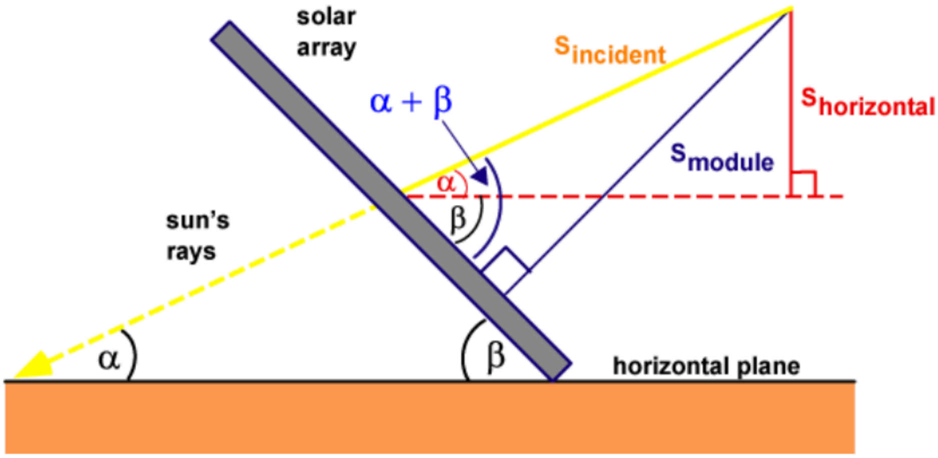


Fig. 3-2: Solar radiation on a tilted surface [6].

For fixed panels the optimum tilt angle is equal to the location's latitude, if this angle is increased the winter production is being optimized and if it is decreased the summer production is optimized.

It is possible to maximize the PV plant generation by installing solar trackers. With a tracking system the panels follow the Sun optimizing the angle at which the cells receive the radiation.

The trackers can be of one (Fig. 3-3) or two axis (Fig. 3-4), the first one moves the panels on one axis, usually aligned with north and south which allows to follow the Sun from east in the morning to west in the afternoon. The two axis trackers are aligned north-south and east-west; this allows to follow the Sun during the day and also to track the seasonal variations in the height of the Sun.

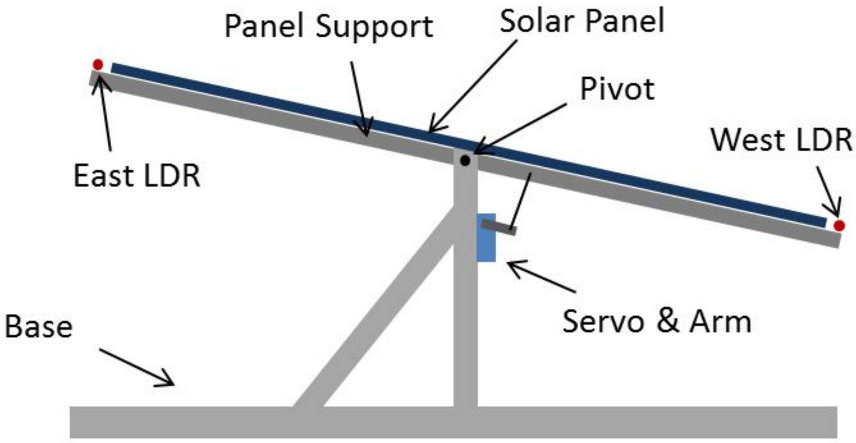


Fig. 3-3: Single axis solar tracker [7].

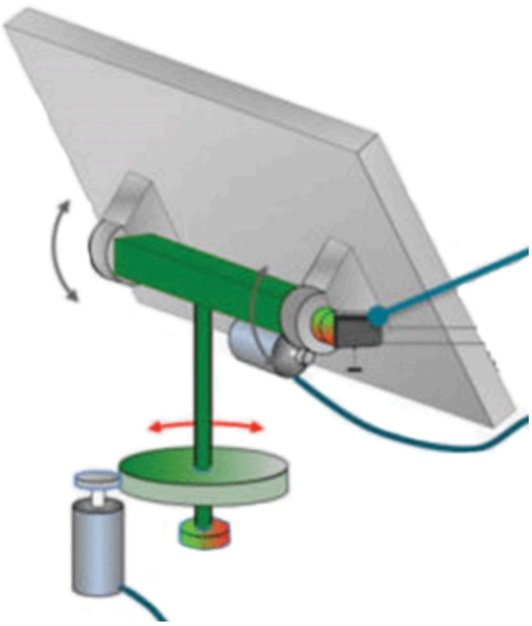


Fig. 3-4: Dual axis solar tracker [8].

4. Photovoltaic fundamentals

A photoelectric cell is an electronic device made of a material that permits to transform the energy of the Sun into electric energy by absorbing the light which creates electrical voltage. This effect, known as the photovoltaic effect, was discovered by the French physicist Edmond Becquerel in 1839 [9].

When the sunlight impacts a PV cell, the photons can be absorbed, reflected or they may pass right through. The energy of the absorbed photons is transferred to electrons in atoms of the semiconductor device [9]. Two different types of semiconductors, an n-type and a p-type compose the solar cells, which together create a p-n junction.

When the solar cell absorbs light of the adequate wavelength, the energy of the photon is transferred to an atom located in the p-n junction of the semiconducting material. If this energy achieves the band gap, which is the minimum amount of energy required, the electron escapes its bound state at the valence band to a higher energy state, known as the conduction band, leaving a hole in the valence band. The added energy that produces the movement of the electron creates two charge carriers, an electron-hole pair that can move free in the conduction band and valence band respectively participating in conduction and allowing the electron of a near atom to move into the empty space left [10].

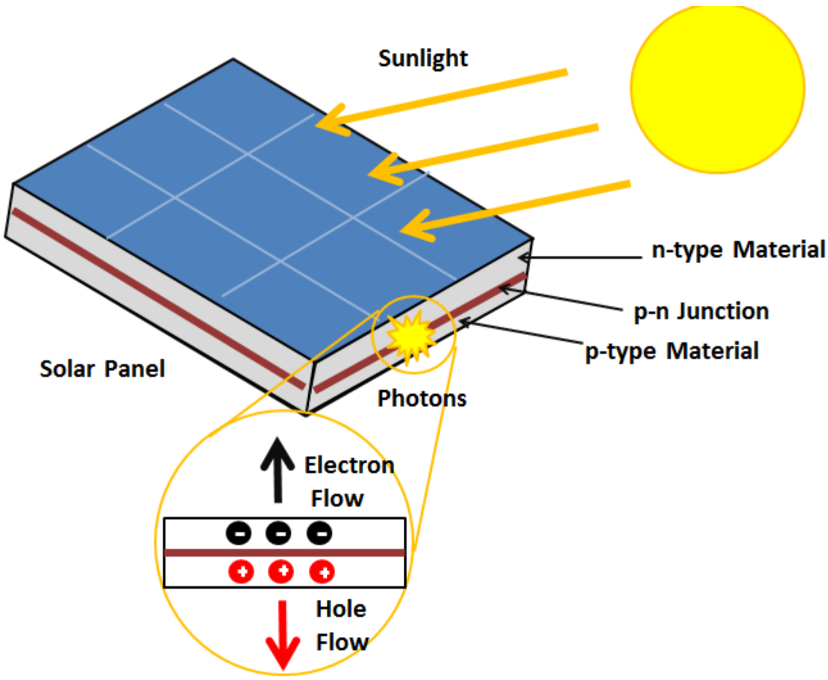


Fig. 4-1: Photovoltaic effect [10].

5. Solar module technologies

Different types of solar cell technologies can be used to convert sunlight into electricity. In power generating applications silicon wafer-based technologies are dominating the photovoltaic energy production.

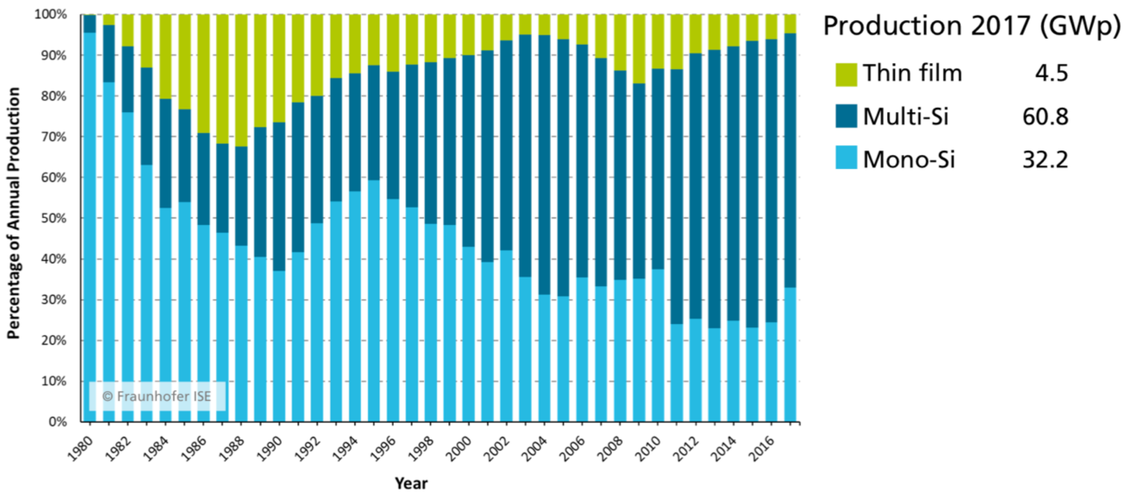


Fig. 5-1: Percentage of global annual production [5].

5.1. Monocrystalline Silicon

Monocrystalline Silicon (Mono-Si) solar cells are made from a unique cylindrical silicon block or ingot. During its fabrication, the Czocharlski process is used, which allows controlling the growth of the silicon crystal to guarantee that the crystal is just formed in one direction, achieving an almost perfect alignment of all its components. This complex process of fabrication explains the higher price of the kind of solar cell. [12]

Between the different types of flat solar panels, panels made from mono-Si, are the ones that convert the highest amount of solar energy into electricity. Nowadays, efficiencies up to 20% have been achieved for commercial mono-Si solar panels [13]. In reference to its life time, nowadays most warranties go for 25 years.

5.2. Polycrystalline Silicon

The production process of polycrystalline solar cells is much simpler and requires less silicon than the production process of monocrystalline cells. Essentially, the molten silicon is poured into a cast instead of being made into a single crystal by applying the Czocharlski process.

In reference to efficiency, polycrystalline panels typically have an efficiency of a 13%-16%, which is about a 70%-80% of a comparable monocrystalline solar panel [14].

Because of its simple production, which reduces costs, and its high efficiency polycrystalline panels have become the most used technology for photovoltaic applications. Its warranty as in the monocrystalline panels arrive in the majority of cases to 25 years.

5.3. Thin Film

Thin film solar panels involve different types of panels, which manufacturing has been done with the main objective of reducing the price of solar cells to make them more competitive. They are called thin-films because it consists of active material layers about 96% less thick than layers of crystalline silicon [15].

There are three common types of thin film solar panels:

- Amorphous Silicon (a-Si)

Amorphous Silicon is the non-crystalline form of silicon; an a-Si solar cell contains 1/300th part of active material than a crystalline-silicon cell. The simpler a-Si cells have a single sequence of p-i-n layers, and suffers a degradation of about 15-35% in their power output when exposed to the Sun. This degradation is produced by the Staebler-Wronski Effect, and reduces the a-Si panel's efficiency from 10% to 7% [16].

- Cadmium Telluride (CdTe)

This technology uses a thin film of CdTe to convert solar energy into electricity with an efficiency rate between 9% and 11% [13]. CdTe based solar cell principal advantage is that the manufacturing process is cheaper than the one for silicon-based solar panels. Nevertheless, there are some issues because of the limited availability of Telluride and the long-term toxic effects of Cadmium [15].

- Copper Indium (Gallium) diSelenide (CIS or CIGS)

Among the thin film technologies, CIS and CIGS are the ones which achieves higher efficiencies, arriving in the case of CIGS modules at efficiencies just below 20% in a laboratory [17] and 15,7% in commercial panels, as NREL verified in 2010 for a one square meter in size module produced by MiaSolé [18].

Instead of the high efficiency of CIGS modules, comparable with poli-Si, this kind of technology observes some manufacturing problems and have high production costs, reducing its competitiveness in the market. Because of that, the main goal for its producers is to reduce CIGS manufacturing costs.

6. Solar Inverters

The purpose of an inverter is to convert the DC output of the solar field to an AC compatible with the electrical grid. For that, the Maximum Power Point Tracking (MPPT) system search the point at which the power output is maximum. This MPP is achieved by selecting the best couple of voltage and current, which varies in function of the solar irradiance and the cell temperature of modules. Then, another electronic device converts the direct current to alternating current.

Depending on the PV plant, there are different inverter configurations. Single phase or multi string inverter, which is used for small or medium rooftop PV Plants. Central inverter, used for the largest PV plants. Micro inverter where each PV module has its own inverter and is used for very small PV plants and finally for small ground or large roof-top plants the most common is use three-phase multistring or mini central inverters.

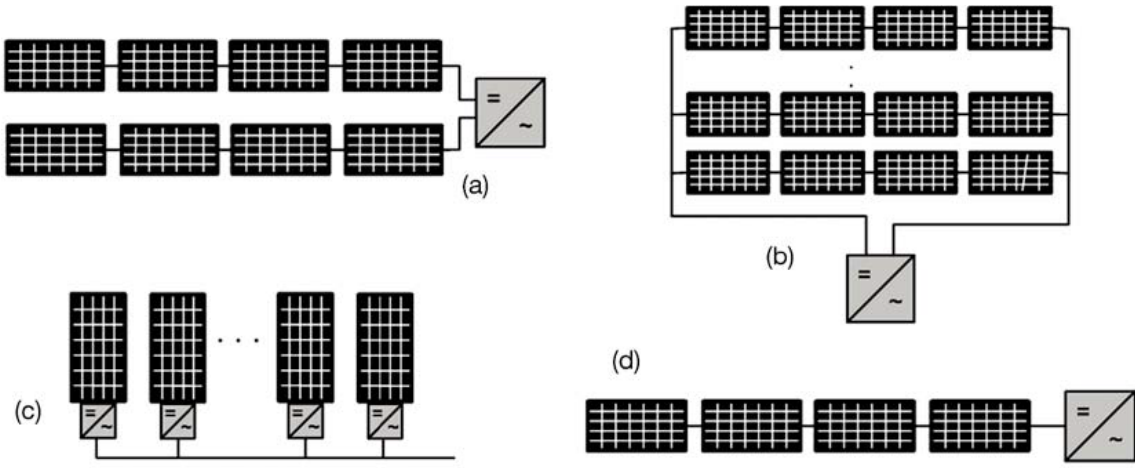


Fig. 6-1: PV Plant connecting configurations; (a) Multi string inverter, (b) Central inverter, (c) Micro inverter, (d) String inverter [19].

In addition, it is important to distinguish between inverters with transformer or without it. For no complex topologies, to install them without a transformer can reduce costs and shall provide higher efficiency.

Another way to classify inverters is based on the number of stages of processing power. Three types of inverters can be distinguished [20]:

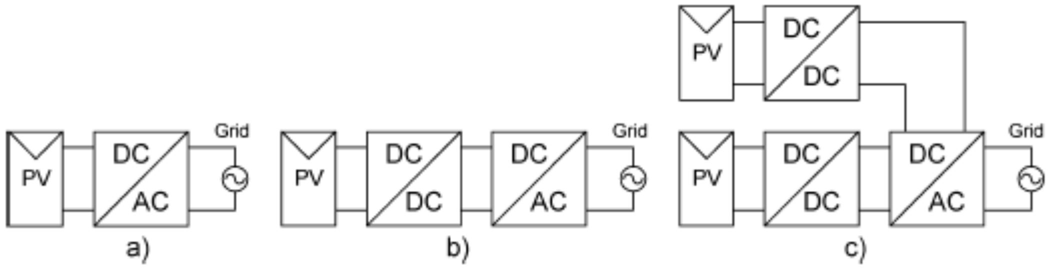


Fig. 6-2: Inverters classification by number of stages [20]

Inverter "a" from Fig. 6-2 is a single stage inverter and is typically used for central inverters. This kind of inverters has to do all the tasks itself, maximum power point tracking, voltage amplification and grid current control. In the same figure the configuration identified as "b" (Fig. 6-2) represents a dual stage inverter, where the MPPT and the voltage amplification is done by the dc-dc converter and the dc-ac inverter handles the current control. The last scheme is designed for multi-string inverter and is very useful for plants with different conditions between the strings. Each dc-dc converter controls the MPPT and the voltage amplification, and then the converters are connected to the dc link of a common dc-ac inverter, which manages the grid current control.

7. European grid code

The European Union stablishes through the Commission Regulation (EU) 2016/631 of 14 April 2016 [1] a network code on requirements for grid connection of generators.
In accordance with this regulation the connection requirements shall apply to new power-generation modules considered significant. The Article 5 of this regulation determines that the power-generation module object of design in this project is significant, because is a connection point below 110 kV and a maximum capacity at or above a threshold proposed by each relevant transmission system operator (TSO).
In this project the threshold considered is stablished by this regulation in its table 1 (see Table 7-1) where a power-generating module of 10MW is stablished in its type B.

Synchronous areas	Limit for maximum capacity threshold from which a power-generating module is of type B	Limit for maximum capacity threshold from which a power-generating module is of type C	Limit for maximum capacity threshold from which a power-generating module is of type D
Continental Europe	1 MW	50 MW	75 MW
Great Britain	1 MW	50 MW	75 MW
Nordic	1,5 MW	10 MW	30 MW
Ireland and Northern Ireland	0,1 MW	5 MW	10 MW
Baltic	0,5 MW	10 MW	15 MW

Table 7-1: Limits for thresholds for type B, C and D power-generating modules [1].

7.1. General requirements for type B power-generation modules

The following requirements had been obtained from articles 13 and 14 of the commission regulation (EU) 2016/631 of 14 of April [1].

7.1.1. Frequency stability

The generation module shall be capable of remaining connected to the network and operate within frequency ranges and time periods specified in the following table (Fig. 7-1).

Synchronous area	Frequency range	Time period for operation
Continental Europe	47,5 Hz-48,5 Hz	To be specified by each TSO, but not less than 30 minutes
	48,5 Hz-49,0 Hz	To be specified by each TSO, but not less than the period for 47,5 Hz-48,5 Hz
	49,0 Hz-51,0 Hz	Unlimited
	51,0 Hz-51,5 Hz	30 minutes

Fig. 7-1: Minimum time period operation for different frequency ranges [1]

7.1.2. Limited frequency sensitive mode – overfrequency (LFSM-O)

LFSM-O is a mode of the power power-generation module at which the active power output is reduced in response to a change in the system frequency above a certain value. In reference to this mode, the following shall apply:

a) The provision of active power frequency response must be activated by the power generation module according to the Fig. 7-2 at range of frequency and droop settings specified by the relevant TSO;
b) The frequency range shall be between 50,2 Hz and 50,5 Hz both included;
c) The drop settings shall be between 2% and 12%.
d) The power frequency response has to be activated by the power generation module with an initial delay as short as possible. If that delay is greater than two seconds, the owner of the facility has to justify the delay, providing technical evidences to the corresponding TSO;
e) The relevant TSO must require to the power generation module that once the minimum regulation level is reached it has to be able of:
    - continue working at this level; or
    - further decreasing active power output;
f) The power generation module must be able to operate stably during LFSM-O. And if LFSM-O is active, its set point will prevail over any other active power setpoints.

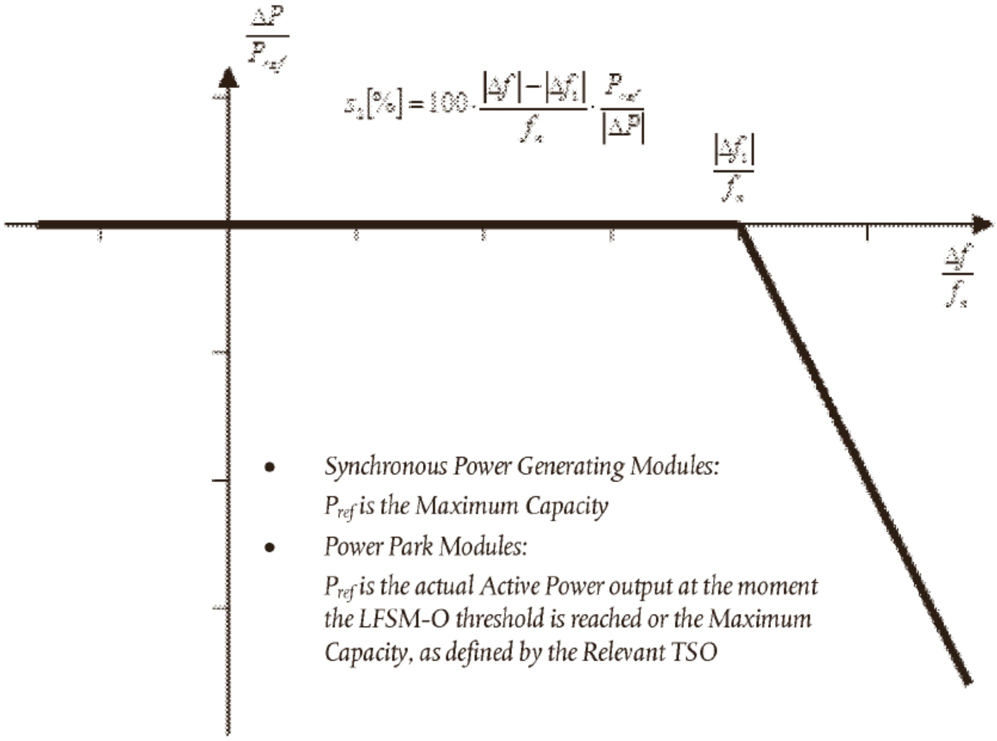


Fig. 7-2: Active power frequency response capability of power-generating modules in LFSM-O [1]

In reference to the previous figure P_{ref} for this project is described for power park modules and is referred to the variation of the active output power (ΔP) of the power generation module. f_n is the nominal frequency of the grid (50Hz) and Δf is the frequency deviation in the network. At over frequencies the power-generation module has to provide a negative active power output variation according with the drop setting S_2.

7.1.3. Active power output

The power-generation module has to be capable of maintaining constant its active power output at its target value regardless of frequency changes, except where the output follows changes specified in the points 6.1.3 and 6.1.4 of this project.

7.1.4. Maximum power capability reduction with falling frequency

The TSO must specify the admissible active power reduction from maximum output respect to the negative variation in the frequency of its control zone as a rate of reduction falling within the boundaries, represented in Fig. 7-3 :

a) Below 49 Hz falling by a reduction of 2% of the maximum capacity at 50 Hz per 1 Hz frequency drop;
b) Below 49,5 Hz falling by a reduction rate of 10% of the maximum capacity at 50 Hz per 1

Hz frequency drop.

This admissible active power reduction shall:

a) Clearly specify the applicable ambient conditions;
b) Take account of the technical capabilities of power-generating modules.

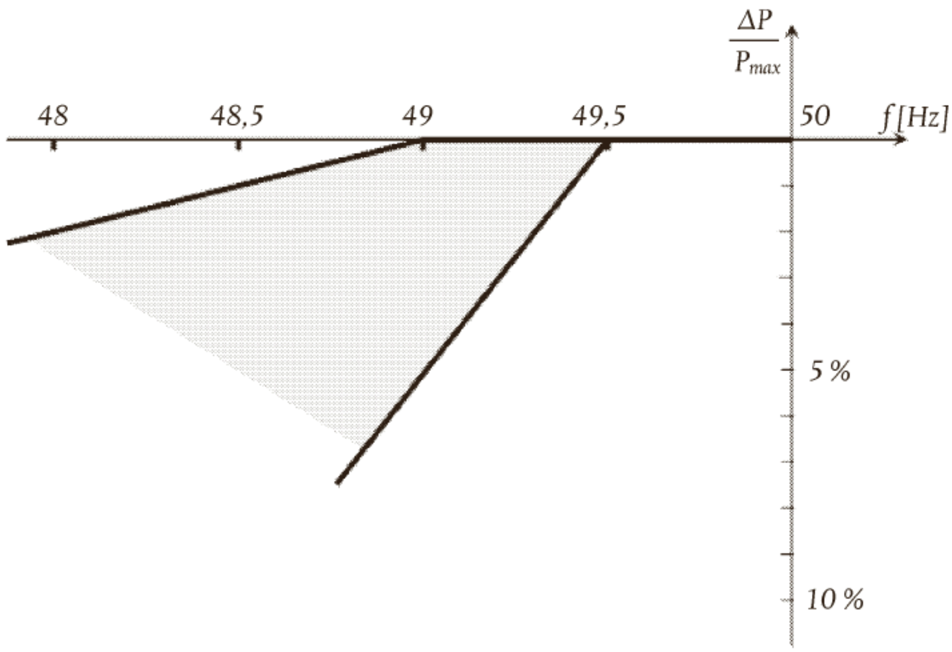


Fig. 7-3: Maximum power capability reduction with falling frequency [1].

7.1.5. Cessation of active power output

The power-generation module has to be equipped with a logic interface to cease the active power output within five seconds since the instruction is received at the input port. The system operator can define the requirements for the equipment to make this facility operable remotely.

7.1.6. Conditions for connecting automatically to the network

Automatic connection is allowed unless the system operator specified otherwise in coordination with the TSO.
Connection conditions shall be specified by the TSO. And must include:

a) Frequency ranges within which the automatic connection to the network is admitted, as well as the corresponding time delay, and
b) The maximum admissible gradient of increase in active power output.

7.1.7. Robustness requirements fault-ride-through

With regard to fault-ride-through capability of power generation modules:

a) Each TSO must specify a voltage-against-time-profile at the connection point for fault conditions according to the Fig. 7-4, that describes in which conditions the power-generating module is able to be connected to the network and continuing operate stably after an electric system disturbance by secured faults on the transmission system. A fault is considered secured when is successfully cleared according to the system operator's criteria.
b) The lower limit of the actual course of the phase-to-phase voltages referred to the voltage level at the point of connection during a symmetrical fault, is described by the voltage-against-time-profile as a function of time before, during and after the fault. This lower limit shall be specified by the relevant TSO using the parameters established in Fig. 7-4 and within the ranges defined in Table 7-2.
c) The relevant TSO shall specify the pre-fault and post-fault conditions for the fault ride through capability in terms of;
    - Calculation of the pre-fault and post-fault minimum short circuit capacity at the connection point,
    - Pre-fault active and reactive power operating point and voltage, at the connection point.

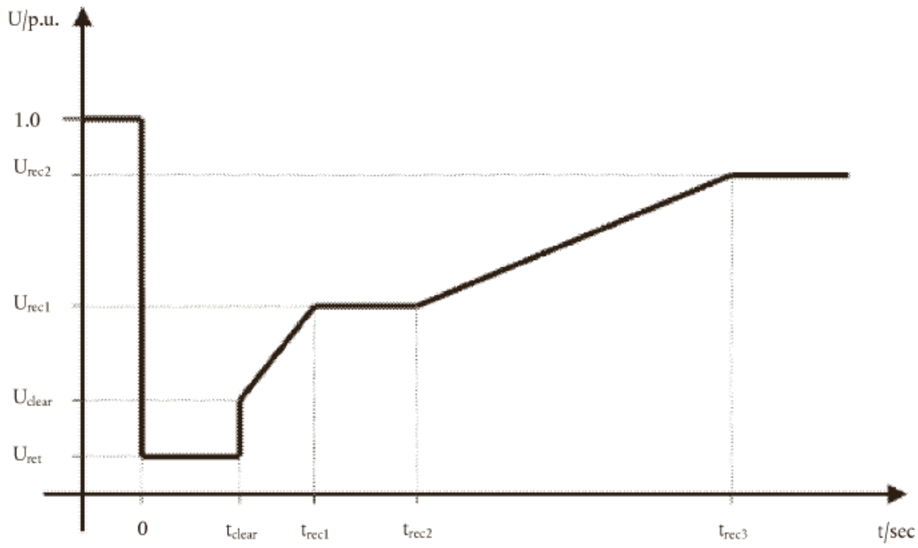


Fig. 7-4: Fault-ride-through profile of a power-generating module [1]

The diagram above (Fig. 7-4) represents the lower limit of a voltage-against-time profile at the connection point. Where U_{ret} is the residual voltage at the connection point during the fault. t_{clear} is the instant at which the fault has been cleared and U_{rec1}, U_{rec2}, t_{rec1}, t_{rec2} and t_{rec3} specify certain recuperation points of lower limits of the voltage after a fault clearance.

Voltage parameters (pu)		Time parameters (seconds)	
U_{ret}:	0,05-0,15	t_{clear}:	0,14-0,15 (or 0,14-0,25 if system protection and secure operation so require)
U_{clear}:	U_{ret}-0,15	t_{rec1}:	t_{clear}
U_{rec1}:	U_{clear}	t_{rec2}:	t_{rec1}
U_{rec2}:	0,85	t_{rec3}:	1,5-3,0

Table 7-2: Parameters for Fig. 7-4 for fault-ride-through capability of power park modules [1]

d) The power-generating-module shall remain working stable and connected to the network when the actual course of the phase-to-phase voltages on the network voltage level at the connection point during a symmetrical fault, given the pre-fault and post-fault conditions in the previous points, remain above the lower limit specified in point 7.1.7 letter (b), unless the protection scheme for internal electrical faults requires the disconnection from the network. These protection schemes must not jeopardize fault-ride-through performance.
e) The undervoltage protection shall be set by the owner of the power-generating facility according to the widest possible technical capability of the power generating module, unless the relevant system operator requires narrower settings in accordance with the electrical protection schemes and settings requirements.
f) Fault-ride-through capabilities in case of asymmetrical faults shall be specified by each TSO.

7.1.8. System restoration requirements

a) The relevant TSO shall specify at which conditions the power-generating-module is capable of reconnecting to the network after an accidental disconnection due to a network disturbance; and
b) The installation of automatic reconnection systems shall be subject to these reconnecting conditions and an to a prior authorization of the relevant TSO.

7.1.9. General system management requirements – control schemes and settings

The different control devices of the power-generating module, and any change on them, shall be coordinated and agreed between the TSO, the relevant system operator and the owner of the power facility;

7.1.10. General system management requirements – protection schemes and settings

a) Considering the characteristics of the power-generating module the relevant system operator shall specify the necessary schemes and settings to protect the network, and them shall be coordinated between the system operator and the power-generating facility owner;

b) Electrical protection of the power-generating module shall take precedence over operational controls, considering the system security and the health and safety of staff and of the public, as well as mitigating any damage to the power-generating module;
c) Any change to the protection schemes and settings shall be agreed between the system operator and the facility owner.

The power-generating facility owner shall organize its protection and control devices according to the priority ranking specified below:

- Network and power-generating module protection;
- Frequency control (active power adjustment);
- Power restriction; and
- Power gradient constraint

7.2. Requirements for power park modules

In addition to the general requirements specified above, the article 20 of the same regulation stablishes the requirements for type B power park modules, and are the following:

7.2.1. Additional voltage stability requirements

a) The relevant system operator shall have the right to specify the capability of a power park module to provide reactive power;
b) the relevant system operator in coordination with the relevant TSO shall have the right to specify that a power park module be capable of providing fast fault current at the connection point in case of symmetrical (3-phase) faults.
c) The relevant system operator in coordination with the relevant TSO shall have the right to specify a requirement for asymmetrical current injection.

7.2.2. Additional robustness requirements

The relevant TSO shall specify the post-fault active power recovery that the power park module has to provide.

8. Spanish grid code

In Spain the sole transmission agent and operator (TSO) is Red Eléctrica de España (REE) and in its publication "*Instalaciones conectadas a la red de transporte peninsular: requisitos mínimos de diseño y equipamiento*" [2] specify the requirements for grid connected power systems in order to ensure the correct operation of the electrical system.

8.1. Energy exchange requirements

8.1.1. Product quality

The product quality refers to the different characteristics of the voltage wave. The most significant characteristics that can affect to the product quality are the following:

- Voltage dips: a voltage dip: a voltage dip is a sudden decrease of the power voltage to a value between 90% and 1% of the nominal voltage of the grid, followed by a voltage restoration after a short time. By agreement, a voltage dip lasts from 10ms to 1 minute. The depth is defined as the difference between the minimum effective voltage during the dip and the nominal voltage. Referred to the voltage dips the power-facilities must be capable of support this voltage values without being damaged.
- Flicker: voltage fluctuations cause variation in the luminance of the lightning. This flicker is an effect associated to visual instability induced by a luminous stimulus which luminosity change with time.
- Harmonics: is defined as the sinusoidal voltage whose frequency is a full multiple of the fundamental frequency of the supply voltage.
- Voltage unbalance: is a voltage variation in a system in which the voltage magnitudes or the phase angle differences between them are not equal.

8.1.2. Planification levels

They are defined as the maximum electromagnetic perturbation levels at which a given grid is designed.

- Flicker according to the International Electrotechnical Commission (IEC) the following levels has been stablished for the transmission network:

  Short term flicker (Pst) ≤ 1,0

  Long term flicker (Pls) ≤ 0,8

  These limits include the transference coefficient form HV to LV, and because of that they shall be compared with the flicker calculated in HV.

- Harmonics. According to the IEC the following planning levels (Table 8-1) must be used, in the transmission network, for harmonic voltages:

Harmonic order (n)	Harmonic ratio (%)	Harmonic order (n)	Harmonic ratio (%)
3	2	2	1,5
5	2	4	1
7	2	6	0,5
9	1	8	0,2
11	1,5	10	0,2
13	1,5	12	0,2
15	0,3	14	0,2
17	1	16	0,2
19	1	18	0,2
21	0,2	20	0,2
23	0,7	22	0,2
25	0,7	>22	0,2
>25	0,2+0,5*25/n		
TOTAL HARMONIC DISTORSION RATE (TDH) 3,00%			

Table 8-1. Harmonic Planning levels

- Voltage unbalance: the planification levels established for the unbalance degree (μ) are function of the duration of the voltage deviation are showed below, and are expressed in as a percentage of the relation between the reverse sequence voltage component (vector magnitude) and the direct sequence voltage component (vector magnitude).

  $\mu \leq$ 1% for deviations with a duration lounger than 10 minutes (short time limit)

  $\mu \leq$ 2% for deviations range during periods up to 10 minutes (very short time limit)

8.1.3. Limits of emission disturbances

These limits refer to the electromagnetic perturbation levels emitted by all the devices or systems connected to a same node and measured according to stablished specification.

- Flicker: the following flicker emission limits have been stablished for each node of the transport grid:

  Pst $\leq$ 0,8

  Pls $\leq$ 0,6

- Harmonics: in order to avoid exceed the planification levels indicated in point 8.1.2, the following emission limits for harmonics voltages have been stablished for each node of the transport grid.

Harmonic order (n)	Harmonic ratio (%)	Harmonic order (n)	Harmonic ratio (%)
3	1,8	2	1
5	1,8	4	0,9
7	1,8	6	0,4
9	0,9	8	0,2
11	1,3	10	0,2
13	1,3	12	0,2
15	0,3	14	0,2
17	0,9	16	0,2
19	0,9	18	0,2
21	0,2	20	0,2
23	0,6	22	0,2
25	0,2	>22	0,2
>25	0,2		
TOTAL HARMONIC DISTORSION RATE (TDH) 3,00%			

Table 8-2: Emission limits for harmonic disturbances [2].

- Voltage unbalance: according to REE the voltage unbalance emitters must not exceed the following values for voltage unbalance in each node of the transport grid:

  $\mu \leq 0{,}7\%$ for values in the range of minutes (short duration limits)

  $\mu \leq 1\%$ for values in the range of seconds (very short duration limits)

8.1.4. Frequency variations

The nominal frequency at which the energy has to be exchanged is of 50Hz and it's considered as normal frequency variations any variation included between 49,85 and 50,15 Hz [3].

8.1.5. Voltage level

In Catalonia the voltage level for medium voltage facilities is stablished in 25 kV.

8.1.6. Protection system for medium voltage devices

The protection system of the facility connected to the grid, must fulfill the items stablished in the document "Criterios Generales de Protección de los Sistemas Eléctricos Insulares y Extrapeninsulares" [30] who explain the equipment requirements of the grid protection systems.

The connection between the generation facility and the transmission system shall have at least an isolating switch that allows the TSO to disconnect the facility in case of emergency.

8.1.7. Connection diagrams between the power plant and the transport grid

According to the stablished by REE there are three basic different types of connection configurations [2]:

- Type A: Through no transport line without transformation (generator or consumer connection)
- Type C: Through transformer no transport:
  - Type C1: Generator or consumer connection.
  - Type C2: Distribution connection.

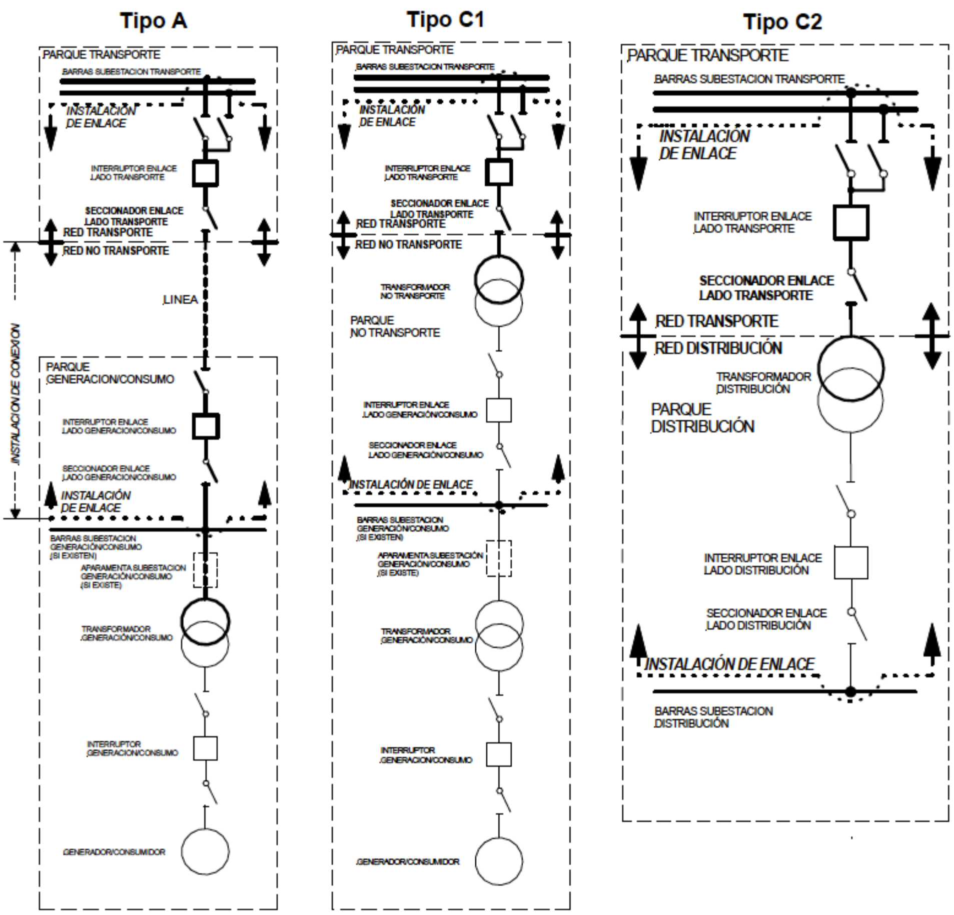


Fig. 8-1: Connection diagrams for grid connected systems [2]

The PV power plant object of study have to be connected with the type C1 configuration, the output of the park transformer will go to a substation property of the TSO and then to the transport grid.

9. The Spanish electric market

In Spain the price of the electricity is stablished by auction. The first which enters in the pool the technology is the one which due to its characteristics sells the electricity at lower prices, followed by next cheaper technology, until the demand is covered. Once the demand is reached, the selling price of electricity to be paid will be the price of the last technology entered in the pool. Therefore, the higher the demand is, the more expensive technologies enter in the pool and the higher the price of electricity.

Last 2018 the average price of electricity in the daily market of the Spanish zone was 57,45€/MWh which represents an increase of 9% respect to 2017 [21]. As it can be seen in the next figure it was higher than in 2017 during 8 months.

Fig. 9-1: Daily market average price. Spanish zone 2017-2018 [21].

According to AleaSoft [22] these high prices observed in 2018 are due to two reasons. The price of the fossil fuels had been high in large part of the year and above everything the price of the emission right of CO_2 has been multiplied by five in the last year and a half. Additionally, the fact that the reservoirs of water were under minimum has allowed the hydroelectric power plants to sell the electricity in moments of high prices, something that does not happen when the reservoirs are full and they have to sell the electricity at a lower price.

Predicting the market price of electricity for the following years is very difficult because it depends on many factors, as explained above. According to the report of the European Commission “Energy prices and costs in Europe” [23], instead of the fact that the increasing renewable penetration will reduce prices in the spot markets, the overall trends for the electricity price remains dominated by the prices of coal and gas, which are very volatile. In reference to the financial evaluation of this project, a price feed in tariff of 57,45 €/MWh with a long-term contract are going to be considered.

10. PV Plant sizing

10.1. Geographical situation

The PV plant is going to be designed to be located in Cabrera de Mar, a village at 35 km North from Barcelona, located in the region of Maresme and with a population of 4.664 inhabitants. The following table (Table 10-1) and figure show the geographical location and satellite view of the village respectively.

Time Zone	UTC + 1
Latitude	41º31'00'' N
Longitude	2º23'59'' E
Altitude	32m

Table 10-1: Geographical data of Cabrera de Mar

Fig. 10-1: Satellite view of Cabrera de Mar [11].

The area surrounded in yellow, located in the lands near the sea, is the place where the PV Plant can be installed. This crop lands are located at 0,5 km from the access to the highway C-32.

10.2. Solar resource and meteorological data

Spain is one of the countries with higher solar radiation. As it can be seen in the following figure (Fig. 10-2) it varies widely from values of direct normal irradiation of around 900 kWh/m^2 in the north of the country to values between 1900 kWh/m^2 and 2200 kWh/m^2 in the greater part of the country.

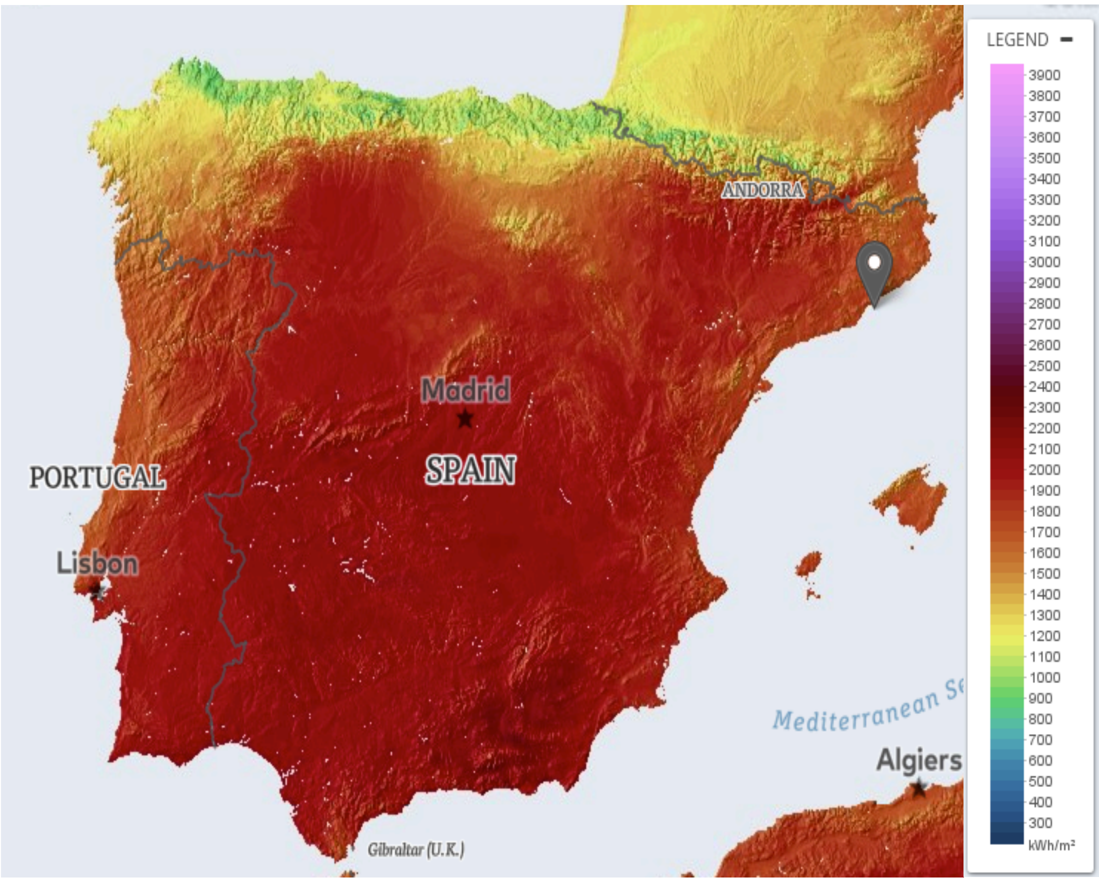


Fig. 10-2. Direct Normal Irradiation [31]

For designing the PV Plant, the meteorological data has been taken from Meteonorm 7.2 (1991-2010). Table 10-2 shows the meteorological data of Cabrera de Mar during a year and Fig. 10-3 shows the temperature variation in the chosen location during the year.

	GlobHor	DiffHor	T_Amb	WindVel	GlobInc	DifSInc	Alb_Inc
	kWh/m²	kWh/m²	°C	m/s	kWh/m²	kWh/m²	kWh/m²
Enero	64.3	23.39	7.83	2.7	108.3	27.94	0.857
Febrero	82.0	35.50	9.05	2.6	117.6	39.92	1.098
Marzo	130.3	46.60	12.05	2.8	161.3	48.64	1.745
Abril	162.7	65.20	14.35	2.9	177.6	64.51	2.177
Mayo	195.5	82.40	18.12	2.6	190.6	77.91	2.617
Junio	201.2	82.62	22.22	2.5	188.8	76.91	2.693
Julio	218.6	76.80	24.47	2.4	208.9	71.99	2.928
Agosto	184.0	72.29	24.54	2.4	190.4	70.18	2.463
Septiembre	140.2	54.40	20.80	2.5	165.2	55.35	1.876
Octubre	103.7	39.40	17.53	2.5	141.7	42.96	1.389
Noviembre	67.6	28.80	11.92	2.7	105.1	33.07	0.904
Diciembre	55.6	23.10	8.42	2.9	97.3	28.38	0.743
Año	1605.7	630.50	15.98	2.6	1853.1	637.77	21.490

Table 10-2. Meteorological data

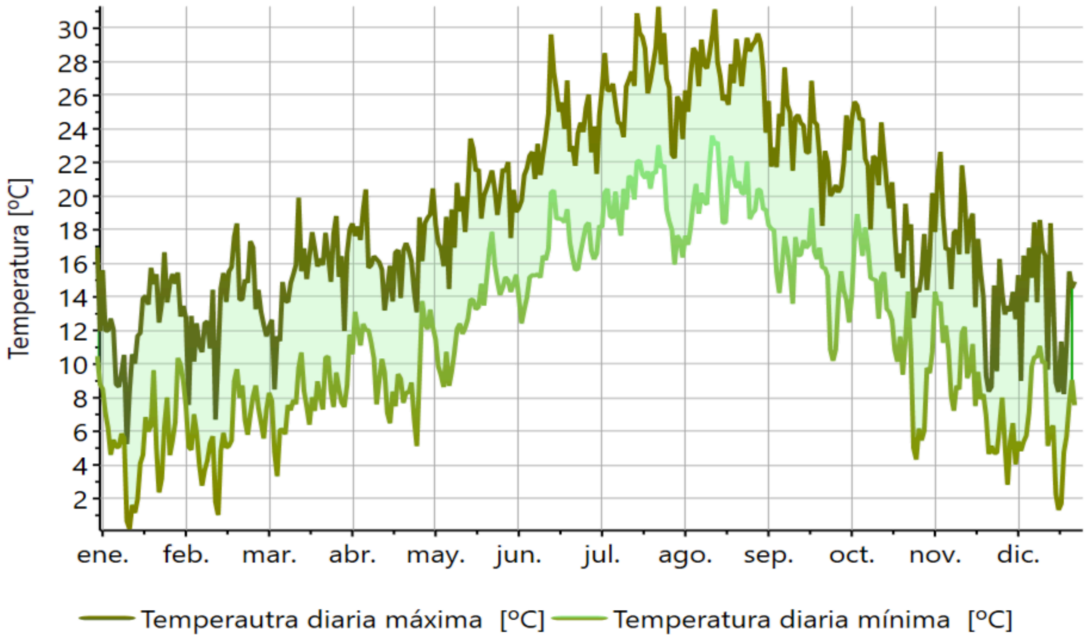


Fig. 10-3. Temperature variation in Cabrera de Mar

10.3. PV Plant component selection

An adequate selection of the PV Plant components is very important in order to warranty the economic feasibility. As general items, performance, cost and warranty are the most important parameters to consider.

10.3.1. PV modules

Focusing in solar panels the criteria that is necessary to consider is the following [33]:

- Solar panel power rating which indicates the power produced under industry STC.
- Power tolerance which indicates how the power output may differ from the nominal power rating, in the power tolerance selection narrower values are preferable because it represents more certainty.
- Solar cell efficiency, this parameter represents how effectively can be converted the solar radiation into electricity.
- Temperature coefficient. Heat reduces the power generation capacity of a solar panel, how this capacity is decreased is quantified by the temperature coefficient. This test is performed in a way that shows how the power capacity is reduced at temperatures above 21ºC. So, a panel with a small temperature coefficient will perform better.
- Solar panel quality. In order to evaluate this parameter is important to choose a product with the ISO 9001 that is a quality assurance standard for manufacturing industry done by the International Organization for Standardization.
- Solar panel durability parameter measures how well the panel will hold over time. The standard that a panel must accomplish to believe the values provided by the manufacturer is the IEC 61215 done by the International Electrotechnical Commission.
- Solar panel warranty. If some problem occurs with the panel after the installation a strong warranty ensures that the service needed to solve it will be covered by the manufacturer.

The chosen PV modules are made by Jinko Solar, one of the leaders in solar industry. Both panels are the same model, but different technologies one monocrystalline and the other polycrystalline. Both are built with 72 solar cells, have an efficiency of 17,52% and a rated power under STC of 340W. Table 10-4 shows the main characteristics of the chosen panels. In Appendix I – Monocrystalline panel data sheet and Appendix II – Polycrystalline panel data sheet, the technical specifications sheet provided by the manufacturer of the modules can be found.

Manufacturer	Jinko Solar	Jinko Solar
Model	JKM340M-72	JKM340PP-72
Country	China	China
Cell Type	Mono-crystalline	Poly-crystalline
No. of cells	72	72
Dimensions	1956x992x40mm	1956x992x40mm
Weight	22,5 kg	22,5 kg
Maximum Power (W)	340W	340W

Manufacturer	Jinko Solar	Jinko Solar
Model	JKM340M-72	JKM340PP-72
Maximum Power Voltage (Vmp)	38,7V	38,2V
Maximum Power Current (Imp)	8,79A	8,91A
Open-circuit Voltage (Voc)	47,1V	47,5V
Short-circuit Current (Isc)	9,24A	9,22A
Module Efficiency STC	17,52%	17,52%
Operating Temperature Range	-40°C~+85°C	-40°C~+85°C
Maximum system voltage	1000 VDC(IEC)	1000VDC(IEC)
Maximum series fuse rating	20A	20A
Power tolerance	0~+3 %	0~+3 %
Temperature coefficients of Pmax (%/ºC)	-0,40 %/ºC	-0,40%/ºC
Temperature coefficients of Voc (%/ºC)	-0,29 %/ºC	-0,31 %/ºC
Temperature coefficients of Isc (%/ºC)	0,048 %/ºC	0,06 %/ºC
Nominal operating cell temperature (NOCT) (ºC)	45±2°C	45±2°C
Price (€)	75,65	66,57

Table 10-3. Technical Data and Price of the PV modules.

For both models the product warranty is of 10 years. The power warranties are of 10 years with a minimum power output of a 90% for both products, and of 25 years with a minimum power output of an 80,7% for the polycrystalline model and 80,2% for the monocrystalline model.

10.3.2. Solar Inverter

In the case of the inverter selection for the PV power plant first is necessary to consider the grid requirements of Spain, considering that parameter the inverter selected to be installed is the SUNNY CENTRAL 2200 from the German manufacturer SMA Solar Technology AG. The inverter elected have a nominal AC output power of 2.200kVA, with a high efficiency (98,6%) and a small total harmonic distortion (THD), less than 3% at nominal power. The table below, Table 10-4, shows the technical data of the inverter:

Model	SC 2200
Input (DC)	
MPP voltage range VDC	570—1000 V
Max. input voltage VDC, max	1,000 V (1,100 IEC)
Max. input current IDC, max (at 25°C / at 50°C)	4,110 A / 3,960 A
Number of DC inputs	24
Max. number of DC cables per DC input (for each polarity)	2 x 800 kcmil, 2 x 400 mm2

ETSEIB

Available DC fuse sizes (per input)	200 A, 250 A, 315 A, 350 A, 400 A, 450 A, 630 A
Output (AC)	
Nominal AC power at cos φ =1 (at 25°C / at 40°C / at 50°C)	2,200 kVA / 2,080 kVA / 2,000 kVA
Nominal AC power at cos φ =0,9 (at 25°C / at 40°C / at 50°C)	1,980 kW / 1,872 kW / 1,800 kW
Max. output current IAC, max	3,300 A
Nominal AC current IAC, nom	3,000 A
Max. total harmonic distortion	< 3% at nominal power
Nominal AC voltage / nominal AC voltage range	385 V / 347—424 V
AC power frequency	50 Hz, 60 Hz
Power factor at rated power / displacement power factor adjustable	1 / 0.8 overexcited to 0.8 underexcited
Efficiency	
Max. efficiency / European efficiency / CEC efficiency	98.6% / 98.3% / 98.0%
Protective Devices	
Input-side disconnection point	DC load-break switch
Output-side disconnection point	AC circuit breaker
DC overvoltage protection	Surge arrester, type II
Degree of protection (as per IEC 60529)	IP54
Degree of protection (as per NEMA)	3R
General Data	
Dimensions (W / H / D)	2,780 / 2,318 / 1,588 mm (108.7 / 90.5 / 65.7 inch)
Weight	< 4,000 kg / < 8,819 lb
Max. self-consumption (operation)3 / self-consumption (standby)	< 8,100 W / < 300 W
Internal auxiliary power supply	Integrated 8.4 kVA transformer
Operating temperature range	-25 ... 60°C / -13 ... 140°F
Extended operating temperature range	○ (-40 ... 60°C / -40 ... 140°F)
Temperature range (standby)	-40 ... 60°C / -40 ... 140°F
Temperature range (storage)	-40 ... 70°C / -40 ... 158°F

Max. permissible value for relative humidity (condensation)	0 ... 100%
Maximum operating altitude above MSL 2,000 m / 4,000 m	● / ○ (with power reduction)
Fresh air consumption	6,500 m3/h
Features	
DC connection	Terminal lug on each input or one busbar (without fuse)
AC connection	With busbar system (three busbars, one per line conductor)
Communication	Ethernet, Ethernet/IP, Modbus Master, Modbus Slave
Communication with SMA string monitor	Ethernet (OF), Modbus
Enclosure / roof color	RAL 9016 / RAL 7004
Display	HMI touchscreen (10.1”)
Supply transformer for external loads	○ (2.5 kVA)
Certificates and approvals	BDEW, EMC FCC Part 15 Class A, UL 1741, UL 1998, UL 840 Category IV, IEEE 1547, CE

Table 10-4. Technical Data of the inverter

The inverter output voltage has to be converted to the voltage level of the medium-voltage grid, 25kV, to send it to a substation. The transformer chosen to do that is the model MVPS2200 from the same manufacturer, to ensure its compatibility with the inverter.
Each inverter will be connected to the grid following the connection diagram type C1, see Fig. 8-1, according to the legislation.

10.4. Costs

Normally the costs of all the elements and materials that are necessary to build the power plant are not published in the manufacturer’s web sites. Due to this complexity to estimate the costs of the PV plant, the data published by the International Energy Agency in its report *National Survey Report of PV Power Applications in SPAIN – 2016”* [34] have been used in this project.

Cost Category	**Average (€/W)**
Hardware	
Inverter - transformer	0,05
Other (wiring, structure, racking, etc.)	0,06
Soft Cost	
Installation	0,13
Operation and Maintenance	0,02

Table 10-5. Average costs for PV Systems > 3MW

To stablish the price of the solar panels the data has been obtained from an article of pv-magazine where an average price of $0,22 and $0,25 per watt was set for polycrystalline and monocrystalline respectively.

10.5. System sizing

In this point the system is going to be sized step by step following the next procedure proposed by SMA in its publication “Planning of a PV Generator” [36].

- Calculate the power dimensions of the PV plant
    - Determine the inverter AC active power and DC input power
    - Define the nominal power ratio (NPR)
- Calculate the voltage dimensions
    - Calculate voltage dimensions at module level
    - Calculate voltage dimensions at string level

10.5.1. Power dimensions of the PV plant

10.5.1.1. Determining AC Active Power

The AC active power send to the grid, at optimum weather conditions, is determined by the planed output AC power of the inverter (2.2MW), the power factor ($cos\varphi$), the apparent power of the inverter and the AC voltage of the grid. The figure below shows the dependence of the AC active power on the power factor.

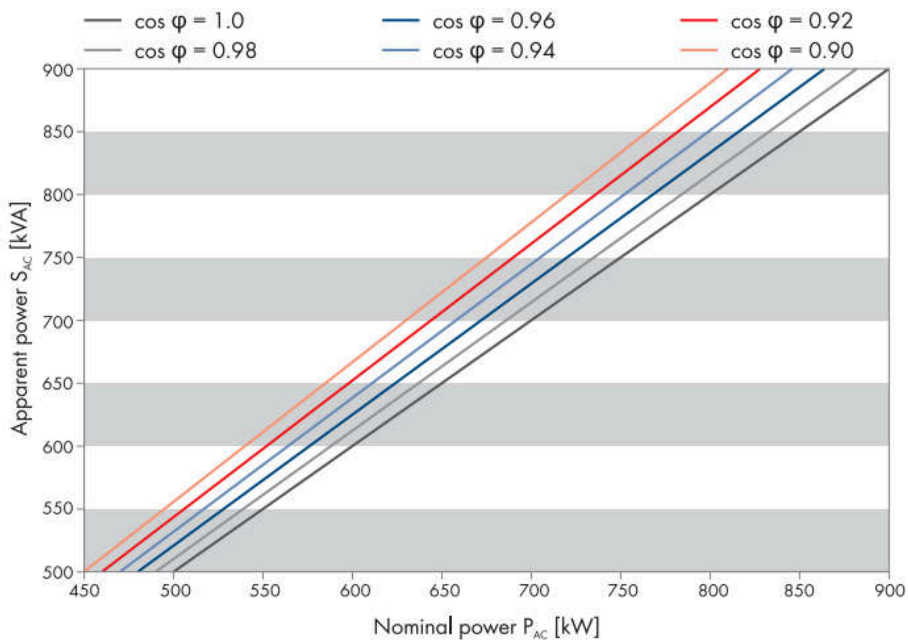


Fig. 10-4: AC active power depending on the power factor $cos\,\varphi$.

The following formula determines the AC active power:

$$P_{AC} = S_{AC} \cdot cos\varphi_{0,9}^{1,0} \qquad \text{(Eq.12)}$$

Where:
P_{AC} = AC active power
S_{AC} = Apparent power of the inverter
$cos\varphi$ = Power factor

$$P_{AC} = 2200\ KVA \cdot 1 = 2200\ kW$$

10.5.1.2. Determining the DC input power of the inverter

The DC input power of the inverter and its efficiency, determines the DC input power required to achieve the desired AC active power that will be fed into the grid. Also, is necessary to mention that the efficiency of the inverter is influenced by the PV array voltage, decreasing with high input voltages.
This input power can be found by using the following equation:

$$P_{DC} = \frac{P_{AC}}{\eta} \qquad \text{(Eq.13)}$$

Where:
P_{DC}: DC input power of inverter
P_{AC}: AC active power
η: Inverter efficiency
The maximum efficiency measured for the inverter elected is of 98,6%.

$$P_{DC} = \frac{2200\ kW}{0,986} = 2231,24\ kW$$

10.5.1.3. Nominal power ratio

This ratio describes the relation between the DC power of the inverter and the DC power of the PV array. Is important to avoid oversizing the inverter because its performance is maximum at certain amount of absorbed power and decreases when this power is small compared with the nominal.
Formula:

$$NPR = \frac{P_{DC}}{P_{DCGEN}} \qquad \text{(Eq.14)}$$

Where:
NPR: Nominal power ratio
P_{DC}: DC power of the inverter
P_{DCGEN}: PV array power

$$NPR = \frac{2231,24\ kW}{2500\ kW} = 0,89$$

The following table summarizes the results obtained in the power dimensioning of the PV plant.

AC Active Power	2200 kW
DC Input Power of the inverter	2231,24 kW
Nominal Power Ratio (NPR)	0,89

Table 10-6: PV plant power dimensions

10.5.2. Voltage dimensions

The electrical performance of the PV panels is affected negatively by the temperature. Affecting this parameter more the voltage than the current, as it can be seen in the figure below. Because of that, items like the module voltage or the string current have to be calculated considering the climate data of the PV location.

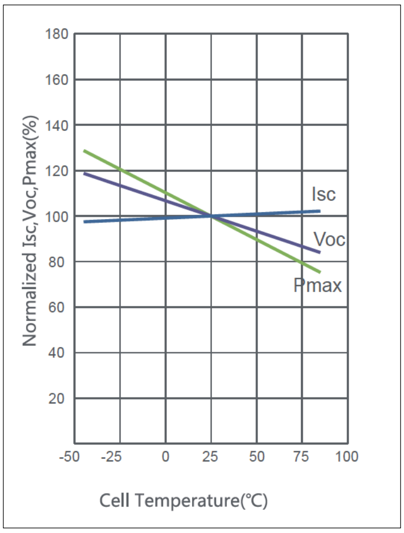


Fig. 10-5: Temperature dependence of I_{SC}, V_{OC} and P_{max}.

10.5.2.1. Maximum open circuit voltage

As can be seen in Fig. 10-5, open circuit voltage decreases with temperature, this dependence leads us to calculate the maximum open circuit voltage, of the module, for the lowest temperature that can be expected at the mounting location.

$$V_{DCmaxMOD} = V_{DCmppMOD(min.T)} = V_{ocM} \cdot \left(1 + \frac{(T_{\min} \cdot \Delta T)}{100\%}\right) \qquad \text{(Eq.15)}$$

Where:
$V_{DCmaxMOD}$: Maximum PV module voltage
V_{ocM}: Open-circuit voltage of the PV module
$T_{\min}$: Temperature coefficient at minimum expected temperature
ΔT: Temperature variance between STC and minimum expected temperature

According to the meteorological data obtained from the NASA Power Access Data Viewer, at the mounting location the lowest temperature registered in the last 10 years is 0,16ºC.

Monocrystalline (JKM340M72):

$$V_{DCmaxMOD} = V_{DCmppMOD(0,16ºC)} = 47,1V \cdot \left(1 + \frac{(-0,29\%\ ºC \cdot (0,16ºC - 25ºC))}{100\%}\right) = 50,493\ V$$

Polycrystalline (JKM340PP72):

$$V_{DCmaxMOD} = V_{DCmppMOD(0,16ºC)} = 47,5V \cdot \left(1 + \frac{(-0,31\%\ ºC \cdot (0,16ºC - 25ºC))}{100\%}\right) = 51,158\ V$$

10.5.2.2. Minimum MPP voltage

To calculate the minimum PV module voltage, it's necessary to consider the highest temperature that can be expected at the mounting location. The highest registered temperature in Cabrera de Mar during the last 10 years is 31,2ºC. Even so, the operation temperatures of the cells use to be between 45ºC and 70ºC. Because of that, is assumed that during the summer the panels will be operating at 70ºC, temperature that will be considered as the maximum expected temperature.

$$V_{DCminMOD} = V_{DCmppMOD(\max.T)} = V_{mpp} \cdot \left(1 + \frac{(T_{\max} \cdot \Delta T)}{100\%}\right) \qquad \text{(Eq.16)}$$

Where:
$V_{DCminMOD}$: Minimum PV module voltage
V_{mpp}: Voltage of the PV module at maximum power
$T_{\min}$: Temperature coefficient at maximum expected temperature
ΔT: Temperature variance between STC and maximum expected temperature

Monocrystalline (JKM340M72):

$$V_{DCminMOD} = V_{DCmppMOD(70ºC)} = 38,7V \cdot \left(1 + \frac{(-0,29\% \cdot (70ºC - 25ºC))}{100\%}\right) = 33,650\ V$$

Polycrystalline (JKM340PP72):

$$V_{DCminMOD} = V_{DCmppMOD(70ºC)} = 38{,}2V \cdot \left(1 + \frac{(-0{,}31\% \cdot (70ºC - 25ºC))}{100\%}\right) = 32{,}871\,V$$

10.5.2.3. Maximum PV module current

As it is seen in the Fig. 10-5 current is less dependent of temperature than voltage, instead of that the maximum PV module current in short-circuit conditions had been calculated considering the maximum expected temperature that can be expected at the installation place.

$$I_{DCmaxSTR} = I_{DCscMOD(70ºC)} = I_{SC} \cdot \left(1 + \frac{(T_{max} \cdot \Delta T)}{100\%}\right) \qquad \text{(Eq.17)}$$

Where:
$I_{DCmaxSTR}$: Maximum string current
I_{SC}: Short-circuit current of the PV module
T_{max}: Temperature coefficient at maximum expected temperature
ΔT: Temperature variance between STC and maximum expected temperature

Monocrystalline (JKM340M72):

$$I_{DCmaxSTR} = I_{DCscMOD(70ºC)} = 9{,}24\,A \cdot \left(1 + \frac{(0{,}048\% \cdot (70 - 25\,ºC))}{100\%}\right) = 9{,}440\,A$$

Polycrystalline (JKM340PP72):

$$I_{DCmaxSTR} = I_{DCscMOD(70ºC)} = 9{,}22\,A \cdot \left(1 + \frac{(0{,}06\% \cdot (70 - 25\,ºC))}{100\%}\right) = 9{,}469\,A$$

In the following table shows the results obtained for the voltage dimensions of the PV plant:

Voltage dimensions		
PV module model	**JKM340M-72**	**JKM340PP-72**
Maximum Open circuit voltage (V)	50,493	51,158
Minimum MPP Voltage (V)	33,650	32,871
Maximum PV Module Current (A)	9,440	9,469

Table 10-7. PV plant voltage dimensions

10.6. String dimensions

10.6.1. Maximum number of PV modules per string

The voltage of a PV modules string must be below the maximum input voltage of the inverter, if it is exceeded yield losses can occur.

$$n_{maxMODSTR} \leq \frac{V_{DCmaxINV}}{V_{DCmaxMOD}} \qquad \text{(Eq.18)}$$

Where:
$n_{maxMODSTR}$: Maximum number of PV modules per string.
$V_{DCmaxINV}$: Maximum input voltage of the inverter
$V_{DCmaxMOD}$: Maximum PV module voltage

Monocrystalline (JKM340M72):

$$n_{maxMODSTR} \leq \frac{1000\,V}{50{,}493\,V} \leq 19{,}81\,modules \sim 19\,modules$$

Polycrystalline (JKM340PP72):

$$n_{maxMODSTR} \leq \frac{1000\,V}{51{,}158\,V} \leq 19{,}54\,modules \sim 19\,modules$$

10.6.2. Minimum number of PV modules per string

To avoid yield losses due to suboptimal MPP tracking is also necessary to maintain the string voltage above de minimum MPP voltage of the inverter.

$$n_{minMODSTR} \geq \frac{V_{DCmppminINV}}{V_{DCminMOD}} \qquad \text{(Eq.19)}$$

Where:
$n_{minMODSTR}$: Minimum number of PV modules per string.
$V_{DCmppminINV}$: Minimum MPP voltage of the inverter
$V_{DCminMOD}$: Minimum PV module voltage

Monocrystalline (JKM340M72):

$$n_{minMODSTR} \geq \frac{570\,V}{33{,}650\,V} \geq 16{,}939\,modules \sim 17\,modules$$

Polycrystalline (JKM340PP72):

$$n_{minMODSTR} \geq \frac{570\,V}{32{,}871\,V} \geq 17{,}340\,modules \sim 18\,modules$$

10.6.3. Number of PV modules per string

The optimum number of photovoltaic modules per string must be between the minimum and maximum as is shown in the following equation:

$$n_{minSTR} \leq n_{STR} \leq n_{maxSTR} \qquad \text{(Eq.20)}$$

Monocrystalline (JKM340M72):

$$17 \leq 19 \leq 19$$

Polycrystalline (JKM340PP72):

$$18 \leq 19 \leq 19$$

10.6.4. Maximum and minimum string voltage

Once the number of modules per string has been stablished, in that case 19 modules per string for both technologies, monocrystalline and polycrystalline, the maximum and minimum string voltage can be calculated by using the following formulas.

$$V_{DCmaxSTR} = n_{MODSTR} \cdot V_{DCmaxMOD} \qquad \text{(Eq.21)}$$
$$V_{DCminSTR} = n_{MODSTR} \cdot V_{DCminMOD} \qquad \text{(Eq.22)}$$

Where:
$V_{DCmaxSTR}$: Maximum voltage per string
$V_{DCminSTR}$: Minimum voltage per string
n_{MODSTR}: Number of modules per string
$V_{DCmaxMOD}$: Maximum PV module Voltage
$V_{DCminMOD}$: Minimum PV module Voltage

These values must be in the MPP voltage range of the inverter, between 570V and 1000V in this case.

Monocrystalline (JKM340M72):

$$V_{DCmaxSTR} = 19 \cdot 50{,}493V = 959{,}365\ V$$

$$V_{DCminSTR} = 19 \cdot 33{,}650V = 639{,}343\ V$$

Polycrystalline (JKM340PP72):

$$V_{DCmaxSTR} = 19 \cdot 51{,}158V = 971{,}996\ V$$

$$V_{DCminSTR} = 19 \cdot 32{,}871\ V = 624{,}551\ V$$

10.6.5. Maximum and minimum number of strings

The maximum number of strings depend on the maximum input current of the inverter, and the minimum depend on the PV array power. They are calculated by using the following equations:

$$n_{maxSTR} = \frac{I_{DCINV}}{I_{DCmaxSTR}} \qquad \text{(Eq.23)}$$

$$n_{minSTR} = \frac{P_{DCGEN}}{P_{maxMOD} \cdot n_{MODSTR}} \qquad \text{(Eq.24)}$$

Where:
n_{maxSTR}: Maximum number of strings
n_{minSTR}: Minimum number of strings
n_{MODSTR}: Number of modules per string
P_{DCGEN}: PV array power
P_{maxMOD}: Maximum PV module power
I_{DCINV}: Maximum input current of the inverter
$I_{DCmaxSTR}$: Maximum string current

Monocrystalline (JKM340M72):

$$n_{maxSTR} \leq \frac{4110\ A}{9{,}440\ A} \leq 435{,}401 \sim 435\ Strings$$

$$n_{minSTR} \geq \frac{2500\ kW}{0{,}340\ kW \cdot 19} \geq 386{,}997 \sim 387\ Strings$$

Polycrystalline (JKM340PP72):

$$n_{maxSTR} \leq \frac{4110\ A}{9{,}469\ A} \leq 434{,}051 \sim 434 Strings$$

$$n_{minSTR} \geq \frac{2500\ kW}{0{,}340\ kW \cdot 19} \geq 386{,}997 \sim 387\ Strings$$

10.6.6. Number of strings per inverter

$$n_{minSTR} \leq n_{STR} \leq n_{maxSTR} \qquad \text{(Eq.25)}$$

Monocrystalline (JKM340M72):

$$387 \leq 435 \leq 435$$

Polycrystalline (JKM340PP72):

$$387 \leq 434 \leq 434$$

Table 10-8 summarizes the results obtained after calculating the string dimensions of the PV plant.

String dimensions		
PV module model	**JKM340M-72**	**JKM340PP-72**
Maximum number of PV modules per String	19,805	19,547
Minimum number of PV modules per String	16,939	17,340
Number of PV Modules per string	**19**	**19**
Maximum string voltage (V)	959,365	971,996
Minimum string Voltage (V)	639,343	624,551
Minimum number of strings	386,997	386,997
Maximum number of strings	435,401	434,051
Number of strings per inverter	**435**	**434**

Table 10-8: PV plant string dimensions

10.6.7. Necessary number of modules for the PV plant

After the previous calculations and considering the results obtained, 4 inverters will be needed for the whole PV system. With the number of modules per string, the number of strings per inverter and the number of inverters, the total number of PV modules needed can be calculated:

$$n_{modules} = n_{MODSTR} \cdot n_{STR} \cdot n_{INV} \qquad \text{(Eq.26)}$$

Monocrystalline (JKM340M72):

$$n_{modules} = 19 \cdot 435 \cdot 4 = 33.060\, modules$$

Polycrystalline (JKM340PP72):

$$n_{modules} = 19 \cdot 434 \cdot 4 = 32.984\, modules$$

Monocrystalline modules perform better with temperature than polycrystalline, which allows to install a higher number of modules than in the system build with polycrystalline technology.

10.7. Yearly energy production of the PV system

To make a first estimation of the PV plant DC energy production of each inverter, the following formula has been used:

$$E_{DC} = P_{DC} \cdot n_{INV} \cdot (PSH) \qquad \text{(Eq.27)}$$

Where:
P_{DC}: Is the DC power of the inverter.
n_{INV}: Is the number of inverters installed.
(PSH): Is the equivalent number of hours at which the solar irradiance average 1000W/m^2.

$$E_{DC} = 2231{,}24 \cdot 4 \cdot 605{,}7 = 5.405{,}842\ MWh\text{/year}$$

In order to calculate the PSH the yearly irradiation showed in Table 10-2, has been used.

$$PSH = \frac{Yearly\ irradiation\ (\frac{kWh}{m^2})}{1000\ W/m^2} \qquad \text{(Eq.28)}$$

$$PSH = \frac{1605{,}7\ (\frac{kWh}{m^2})}{1000\ W/m^2} = 605{,}7\ h$$

To calculate the AC yearly energy production is necessary to consider the efficiency of the inverter:

$$E_{AC} = E_{DC} \cdot \eta_{INV} \qquad \text{(Eq.29)}$$

$$E_{AC} = 5.405{,}842 \cdot 0{,}986 = 5.330{,}160\ MWh/year$$

For the four inverters the total estimated energy production is of 21.320,64 MWh/year.

ETSEIB

11. Grid – Connected PV System Simulation

The previous chapter show the main calculations that are necessary to make the sizing of the PV system. Nevertheless, to obtain more accurate results it is necessary to make a simulation by using a software. The simulations of this project have been done with the software PV SYST V6.78. This software allows the user to make a simple pre-sizing to obtain a rapid study of a PV installation or to make a more precise project design with a complete study and analysis of the project.

For an accurate sizing the Project Design Grid-Connected option have been used, as well as the data base of the software. The data base includes meteorological data and PV Plant elements data.

Fig. 11-1: PV SYST dashboard for system parameters

Once the type of system has been selected the project design is done in different steps:

- Select the location of the system from the meteorological data base.
- Define the parameters of the project as the albedo and the design conditions. The working temperatures must be specified in the design conditions.
- In the orientation parameter stablish the type of PV field, if it is done by fixed panels, single axis solar tracking or double axis solar tracking. Then is necessary to specify the inclination of the panels and the azimuth.
- Select the system components, PV module and inverter model. In the same dashboard

it is also recommended to specify the desired power of the system and if it is going to be distributed in one or more subsets.

- Is necessary to consider losses of the different components of the system, modules, cables and transformer.
- Introduce economical parameters. Capital expenditures, operation and maintenance expenditures.

After introducing all the parameters for the two technologies object of study the simulation can be done, obtaining the results of the simulations. With these results is possible to compare between the two different systems.

First of all is necessary to mention that both systems have been designed dividing them in for fields or subsets of 2.500kWp installed each, one for each inverter.

11.1. Monocrystalline technology simulation

The results, obtained after simulating the monocrystalline grid connected PV system, shows that for each field is necessary to install 387 strings with 19 modules in series. For this system 29412 modules will be needed and are going to be installed in at least a total area of 57070m^2. The losses considered are related to the component selection, as well as the auxiliary losses, or consumption, of the inverter. Fig. 11-2 and Fig. 11-3 show the parameters of the simulation and the characteristics of the four fields.

The main results of the monocrystalline grid-connected PV System are shown in Fig. 11-4. In the main results the estimated energy production during a year and the economical parameters as CAPEX and OPEX. Related to the energy production, as can be seen in the figure, the month with higher production is July that is the month with more irradiation.

Fig. 11-5 show the economic evaluation for the monocrystalline grid-connected PV system. The total CAPEX is of 4.600.036,80 EUR, which includes the cost of the PV modules (2.200.017,60 EUR), the cost of the inverters (500.004,00 EUR), the cost of installation (1.300.010,40 EUR) and an overall cost for structure, wiring and other components (600.004,80 EUR).
The OPEX cost of this system is of 223789,51 EUR/year including an inflation of a 1%.
Also, the necessity of a loan, that is going to be paid in 20 years, has been considered. With an interest rate of a 3% each year 309.194,73 EUR/year must be paid in this concept. So, the total yearly cost of the plant will be 471.145,29 EUR/year.
Finally, and according to the estimated energy production is possible to know the cost of each kWh of energy produced (0,04 EUR/kWh).

Sistema Conectado a la Red: Parámetros de la simulación

Proyecto :	**10MW Grid-Connected PV System (monocrystalline)**			
Sitio geográfico	**Cabrera de Mar**		País	**Espana**
Ubicación	Latitud	41.52° N	Longitud	2.41° E
Tiempo definido como	Hora Legal	Huso horario UT+1	Altitud	13 m
	Albedo	0.20		
Datos meteorológicos:	**Cabrera de Mar**	Meteonorm 7.2 (1991-2010), Sat=43% - Sintético		

Variante de simulación :	**Nueva variante de simulación**	
	Fecha de simulación	29/04/19 10h55
	Simulación para la	**25.° año de funcionamiento**

Parámetros de la simulación	Tipo de sistema	**No hay escenario 3D, no hay sombreados**		
Orientación plano captador	Inclinación	41°	Acimut	0°
Modelos empleados	Transposición	Hay	Difuso	Perez, Meteonorm
Horizonte	Sin horizonte			
Sombreados cercanos	Sin sombreado			
Necesidades del usuario :	Carga ilimitada (red)			

Características de los conjuntos FV (4 Tipo de conjunto definido)

Módulo FV	Si-mono	Modelo	**JKM 340M-72**		
Base de datos Pvsyst original		Fabricante	Jinkosolar		
Sub-conjunto "Sub-conjunto #1"					
Número de módulos FV		En serie	19 módulos	En paralelo	387 cadenas
Núm. total de módulos FV		Núm. módulos	7353	Pnom unitaria	340 Wp
Potencia global del conjunto		Nominal (STC)	**2500 kWp**	En cond. de funciona.	2257 kWp (50°C)
Caract. funcionamiento del conjunto (50°C)		U mpp	664 V	I mpp	3397 A
Sub-conjunto "Sub-conjunto #2"					
Número de módulos FV		En serie	19 módulos	En paralelo	387 cadenas
Núm. total de módulos FV		Núm. módulos	7353	Pnom unitaria	340 Wp
Potencia global del conjunto		Nominal (STC)	**2500 kWp**	En cond. de funciona.	2257 kWp (50°C)
Caract. funcionamiento del conjunto (50°C)		U mpp	664 V	I mpp	3397 A
Sub-conjunto "Sub-conjunto #3"					
Número de módulos FV		En serie	19 módulos	En paralelo	387 cadenas
Núm. total de módulos FV		Núm. módulos	7353	Pnom unitaria	340 Wp
Potencia global del conjunto		Nominal (STC)	**2500 kWp**	En cond. de funciona.	2257 kWp (50°C)
Caract. funcionamiento del conjunto (50°C)		U mpp	664 V	I mpp	3397 A
Sub-conjunto "Sub-conjunto #4"					
Número de módulos FV		En serie	19 módulos	En paralelo	387 cadenas
Núm. total de módulos FV		Núm. módulos	7353	Pnom unitaria	340 Wp
Potencia global del conjunto		Nominal (STC)	**2500 kWp**	En cond. de funciona.	2257 kWp (50°C)
Caract. funcionamiento del conjunto (50°C)		U mpp	664 V	I mpp	3397 A
Total	Potencia global conjuntos	Nominal (STC)	**10000 kWp**	Total	29412 módulos
		Superficie módulos	**57070 m²**	Superficie célula	50265 m²
Inversor		Modelo	**Sunny Central 2200**		
Base de datos Pvsyst original		Fabricante	SMA		
Características		Voltaje de funcionam.	570-950 V	Pnom unitaria	2200 kWac
Sub-conjunto "Sub-conjunto #1"		Núm. de inversores	1 unidades	Potencia total	2200 kWac
				Relación Pnom	1.14

Fig. 11-2: 10MW Grid-Connected PV System (Monocrystalline). Simulation parameters.

Sistema Conectado a la Red: Parámetros de la simulación

Sub-conjunto "Sub-conjunto #2"	Núm. de inversores	1 unidades	Potencia total	2200 kWac
			Relación Pnom	1.14
Sub-conjunto "Sub-conjunto #3"	Núm. de inversores	1 unidades	Potencia total	2200 kWac
			Relación Pnom	1.14
Sub-conjunto "Sub-conjunto #4"	Núm. de inversores	1 unidades	Potencia total	2200 kWac
			Relación Pnom	1.14
Total	Núm. de inversores	4	Potencia total	8800 kWac

Factores de pérdida del conjunto FV

Suciedad del conjunto			Fracción de pérdidas	3.0 %
Factor de pérdidas térmicas	Uc (const)	20.0 W/m²K	Uv (viento)	0.0 W/m²K / m/s
Pérdida óhmica en el Cableado	Conjunto#1	3.3 mOhm	Fracción de pérdidas	1.5 % en STC
	Conjunto#2	3.3 mOhm	Fracción de pérdidas	1.5 % en STC
	Conjunto#3	3.3 mOhm	Fracción de pérdidas	1.5 % en STC
	Conjunto#4	3.3 mOhm	Fracción de pérdidas	1.5 % en STC
	Global		Fracción de pérdidas	1.5 % en STC
Pérdida Calidad Módulo			Fracción de pérdidas	-0.8 %
Pérdidas de "desajuste" Módulos			Fracción de pérdidas	1.0 % en MPP
Pérdidas de "desajuste" cadenas			Fracción de pérdidas	0.10 %
Deterioro promedio de los módulos	Año núm.	25	Factor de pérdidas	0.4 %/año
Desajuste debido al deterioro	Dispersión RMS sobre Imp	0.4 %/año	Dispersión RMS sobre Vmp	0.4 %/año
Efecto de incidencia, parametrización ASHRAE	IAM =	1 - bo (1/cos i - 1)	Parám. bo	0.05
Pérdidas auxiliares	Constant during operation	8.00 kW	... del umbral de potencia	17608.0 kW

Fig. 11-3. 10MW Grid-Connected PV System (Monocrystalline). Simulation parameters (2).

Sistema Conectado a la Red: Resultados principales

Proyecto : **10MW Grid-Connected PV System (monocrystalline)**

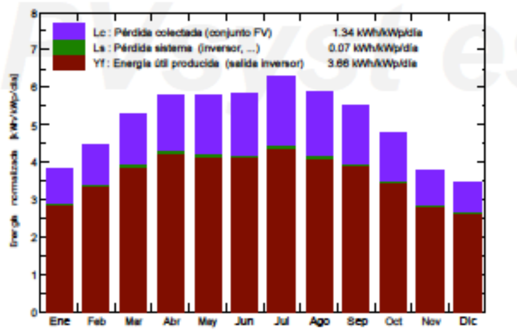
Variante de simulación : **Nueva variante de simulación**
Simulación para la 25.° año de funcionamiento

Parámetros principales del sistema — Tipo de sistema: **No hay escenario 3D, no hay sombreados**
Orientación Campos FV — inclinación: 41° — acimut: 0°
Módulos FV — Modelo: JKM 340M-72 — Pnom: 340 Wp
Conjunto FV — Núm. de módulos: 29412 — Pnom total: **10000 kWp**
Inversor — Modelo: Sunny Central 2200 — Pnom: 2200 kW ac
Paquete de inversores — Núm. de unidades: 4.0 — Pnom total: **8800 kW ac**
Necesidades del usuario — Carga ilimitada (red)

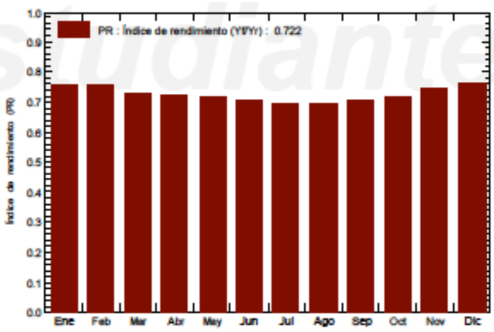
Resultados principales de la simulación
Producción del sistema — **Energía producida**: **13348 MWh/año** — Produc. específica: 1335 kWh/kWp/año
Índice de rendimiento (PR): **72.19 %**

Inversión — Total incl. impuestos: 4600036.80 EUR — Específico: 0.46 EUR/Wp
Costo anual — Anualidades (Préstamo 3.00%, 20 años): 309194.73 EUR/año — Costo de explotación: 200001.60 EUR/año
Costo de energía: **0.04 EUR/kWh** — Payback period: **10.4 años**

Producciones normalizadas (por kWp instalado): Potencia nominal 10000 kWp



Índice de rendimiento (PR)



Nueva variante de simulación
Balances y resultados principales

	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray MWh	E_Grid MWh	PR
Enero	64.3	23.39	7.83	118.6	112.5	910	893	0.753
Febrero	82.0	35.50	9.05	124.5	117.9	958	941	0.756
Marzo	130.3	46.60	12.05	164.1	155.2	1223	1201	0.732
Abril	162.7	65.20	14.35	173.8	163.5	1286	1263	0.727
Mayo	195.5	82.40	18.12	179.8	168.4	1311	1288	0.717
Junio	201.2	82.62	22.22	175.6	164.3	1259	1237	0.704
Julio	218.6	76.80	24.47	195.2	183.0	1379	1356	0.694
Agosto	184.0	72.29	24.54	182.8	171.8	1293	1271	0.695
Septiembre	140.2	54.40	20.80	165.7	156.4	1191	1171	0.707
Octubre	103.7	39.40	17.53	148.1	140.4	1087	1068	0.721
Noviembre	67.6	28.80	11.92	113.4	107.5	858	842	0.743
Diciembre	55.6	23.10	8.42	107.5	102.0	832	817	0.760
Año	1605.7	630.50	15.98	1848.9	1743.1	13586	13348	0.722

Leyendas:
GlobHor — Irradiación global horizontal
DiffHor — Irradiación difusa horizontal
T_Amb — Temperatura Ambiente
GlobInc — Global incidente plano receptor
GlobEff — Global efectivo, corr. para IAM y sombreados
EArray — Energía efectiva en la salida del conjunto
E_Grid — Energía inyectada en la red
PR — Índice de rendimiento

Fig. 11-4. 10MW Grid-Connected PV System (Monocrystalline). Main results.

PVSYST V6.78	Lucas Sastre Pujol (Spain)	29/04/19	Página 6/9

Sistema Conectado a la Red: Evaluación económica

Proyecto : **10MW Grid-Connected PV System (monocrystalline)**

Variante de simulación : **Nueva variante de simulación**

Simulación para la 25.° año de funcionamiento

Parámetros principales del sistema	Tipo de sistema	**No hay escenario 3D, no hay sombreados**		
Orientación Campos FV	inclinación	41°	acimut	0°
Módulos FV	Modelo	JKM 340M-72	Pnom	340 Wp
Conjunto FV	Núm. de módulos	29412	Pnom total	**10000 kWp**
Inversor	Modelo	Sunny Central 2200	Pnom	2200 kW ac
Paquete de inversores	Núm. de unidades	4.0	Pnom total	**8800 kW ac**
Necesidades del usuario	Carga ilimitada (red)			

Inversión

Direct costs			
Módulos FV	7353 unidades	299.20 EUR / unidad	2200017.60 EUR
Inversores			500004.00 EUR
Installation			1300010.40 EUR
Other (wiring, structure, racking, etc.)			600004.80 EUR
		Inversión neta (CAPEX)	**4600036.80 EUR**

Operating costs

OPEX	200001.60 EUR / año
Total (OPEX)	**200001.60 EUR / año**
Operating costs (OPEX) incl. Inflation (1.00%)	**223789.51 EUR / año**

Resumen del sistema

Inversión neta	**4600036.80 EUR**
Own funds	0.00 EUR
Préstamo (20 años) Tasa 3.00 % / año Anualidades 309194.73 EUR / año	4600036.80 EUR
Costo total anual (inc. inflation 1.00 % / año)	**471145.29 EUR / año**
Energía producida	**13348 MWh / año**
Costo de la energía producida	**0.04 EUR / kWh**
(sum of costs over lifetime / total production over lifetime)	

Fig. 11-5. 10MW Grid-Connected PV System (Monocrystalline). Economical results.

11.2. Polycrystalline technology simulation

The results, obtained after simulating the polycrystalline grid connected PV system, shows that for each field is necessary to install 387 strings with 19 modules in series. For this system 29412 modules will be needed and are going to be installed in at least a total area of 57070m^2. The losses considered are related to the component selection, as well as the auxiliary losses, or consumption, of the inverter. Fig. 11-6 and Fig. 11-7 show the parameters of the simulation and the characteristics of the four fields.

The main results of the monocrystalline grid-connected PV System are shown in Fig. 11-8. In the main results the estimated energy production during a year and the economical parameters as CAPEX and OPEX. Related to the energy production, as can be seen in the figure, the month with higher production is July that is the month with more irradiation.

Fig. 11-9 show the economic evaluation for the monocrystalline grid-connected PV system. The total CAPEX is of 4.358.034,86 EUR, which includes the cost of the PV modules (1.985.015,66 EUR), the cost of the inverters (500.004,00 EUR), the cost of installation (1.300.010,40 EUR) and an overall cost for structure, wiring and other components (600.004,80 EUR).
The OPEX cost of this system is of 223789,51 EUR/year including an inflation of a 1%.
Also, the necessity of a loan, that is going to be paid in 20 years, has been considered. With an interest rate of a 3% each year 292.928,40 EUR/year must be paid in this concept. So, the total yearly cost of the plant will be 458.132,23 EUR/year.
Finally, and according to the estimated energy production is possible to know the cost of each kWh of energy produced (0,03 EUR/kWh).

Sistema Conectado a la Red: Parámetros de la simulación

Proyecto : **10MW Grid-Connected PV System (polycrystalline)**

Sitio geográfico	**Cabrera de Mar**		País	**España**
Ubicación	Latitud	41.52° N	Longitud	2.41° E
Tiempo definido como	Hora Legal	Huso horario UT+1	Altitud	13 m
	Albedo	0.20		
Datos meteorológicos:	**Cabrera de Mar**	Meteonorm 7.2 (1991-2010), Sat=43% - Sintético		

Variante de simulación : **Nueva variante de simulación**

	Fecha de simulación	29/04/19 14h48
	Simulación para la	**25.° año de funcionamiento**

Parámetros de la simulación	Tipo de sistema	**No hay escenario 3D, no hay sombreados**		
Orientación plano captador	Inclinación	41°	Acimut	0°
Modelos empleados	Transposición	Hay	Difuso	Perez, Meteonorm
Horizonte	Sin horizonte			
Sombreados cercanos	Sin sombreado			
Necesidades del usuario :	Carga ilimitada (red)			

Características de los conjuntos FV (4 Tipo de conjunto definido)

Módulo FV Si-poly	Modelo	**JKM 340PP-72**		
Base de datos Pvsyst original	Fabricante	Jinkosolar		
Sub-conjunto "Sub-conjunto #1"				
Número de módulos FV	En serie	19 módulos	En paralelo	387 cadenas
Núm. total de módulos FV	Núm. módulos	7353	Pnom unitaria	340 Wp
Potencia global del conjunto	Nominal (STC)	**2500 kWp**	En cond. de funciona.	2262 kWp (50°C)
Caract. funcionamiento del conjunto (50°C)	U mpp	665 V	I mpp	3401 A
Sub-conjunto "Sub-conjunto #2"				
Número de módulos FV	En serie	19 módulos	En paralelo	387 cadenas
Núm. total de módulos FV	Núm. módulos	7353	Pnom unitaria	340 Wp
Potencia global del conjunto	Nominal (STC)	**2500 kWp**	En cond. de funciona.	2262 kWp (50°C)
Caract. funcionamiento del conjunto (50°C)	U mpp	665 V	I mpp	3401 A
Sub-conjunto "Sub-conjunto #3"				
Número de módulos FV	En serie	19 módulos	En paralelo	387 cadenas
Núm. total de módulos FV	Núm. módulos	7353	Pnom unitaria	340 Wp
Potencia global del conjunto	Nominal (STC)	**2500 kWp**	En cond. de funciona.	2262 kWp (50°C)
Caract. funcionamiento del conjunto (50°C)	U mpp	665 V	I mpp	3401 A
Sub-conjunto "Sub-conjunto #4"				
Número de módulos FV	En serie	19 módulos	En paralelo	387 cadenas
Núm. total de módulos FV	Núm. módulos	7353	Pnom unitaria	340 Wp
Potencia global del conjunto	Nominal (STC)	**2500 kWp**	En cond. de funciona.	2262 kWp (50°C)
Caract. funcionamiento del conjunto (50°C)	U mpp	665 V	I mpp	3401 A
Total Potencia global conjuntos	Nominal (STC)	**10000 kWp**	Total	29412 módulos
	Superficie módulos	57070 m²	Superficie célula	51535 m²
Inversor	Modelo	**Sunny Central 2200**		
Base de datos Pvsyst original	Fabricante	SMA		
Características	Voltaje de funcionam.	570-950 V	Pnom unitaria	2200 kWac
Sub-conjunto "Sub-conjunto #1"	Núm. de inversores	1 unidades	Potencia total	2200 kWac
			Relación Pnom	1.14

Fig. 11-6. 10MW Grid-Connected PV System (Polycrystalline). Simulation parameters.

Sistema Conectado a la Red: Parámetros de la simulación

Sub-conjunto "Sub-conjunto #2"	Núm. de inversores	1 unidades	Potencia total	2200 kWac
			Relación Pnom	1.14
Sub-conjunto "Sub-conjunto #3"	Núm. de inversores	1 unidades	Potencia total	2200 kWac
			Relación Pnom	1.14
Sub-conjunto "Sub-conjunto #4"	Núm. de inversores	1 unidades	Potencia total	2200 kWac
			Relación Pnom	1.14
Total	Núm. de inversores	4	Potencia total	8800 kWac

Factores de pérdida del conjunto FV

Suciedad del conjunto			Fracción de pérdidas	3.0 %
Factor de pérdidas térmicas	Uc (const)	20.0 W/m²K	Uv (viento)	0.0 W/m²K / m/s
Pérdida óhmica en el Cableado	Conjunto#1	3.3 mOhm	Fracción de pérdidas	1.5 % en STC
	Conjunto#2	3.3 mOhm	Fracción de pérdidas	1.5 % en STC
	Conjunto#3	3.3 mOhm	Fracción de pérdidas	1.5 % en STC
	Conjunto#4	3.3 mOhm	Fracción de pérdidas	1.5 % en STC
	Global		Fracción de pérdidas	1.5 % en STC
Pérdida Calidad Módulo			Fracción de pérdidas	-0.8 %
Pérdidas de "desajuste" Módulos			Fracción de pérdidas	1.0 % en MPP
Pérdidas de "desajuste" cadenas			Fracción de pérdidas	0.10 %
Deterioro promedio de los módulos	Año núm.	25	Factor de pérdidas	0.4 %/año
Desajuste debido al deterioro	Dispersión RMS sobre Imp	0.4 %/año	Dispersión RMS sobre Vmp	0.4 %/año
Efecto de incidencia, parametrización ASHRAE	IAM =	1 - bo (1/cos i - 1)	Parám. bo	0.05
Pérdidas auxiliares	Constant during operation	8.00 kW	... del umbral de potencia	17608.0 kW

Fig. 11-7. 10MW Grid-Connected PV System (Polycrystalline). Simulation parameters (2).

Sistema Conectado a la Red: Resultados principales

Proyecto : **10MW Grid-Connected PV System (polycrystalline)**

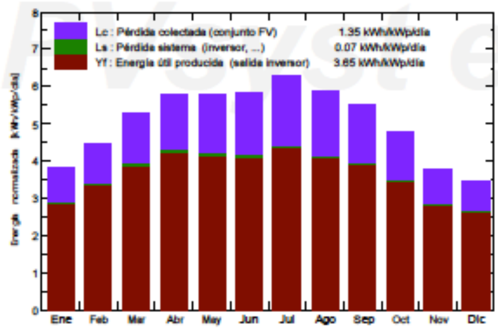
Variante de simulación : **Nueva variante de simulación**

Simulación para la 25.° año de funcionamiento

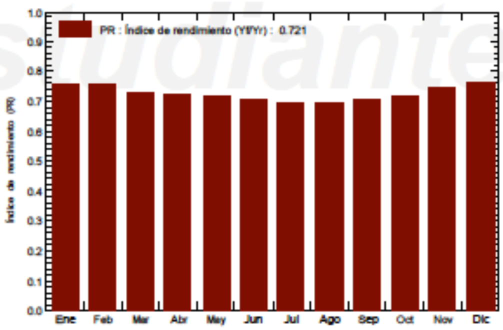
Parámetros principales del sistema	Tipo de sistema	**No hay escenario 3D, no hay sombreados**		
Orientación Campos FV	inclinación	41°	acimut	0°
Módulos FV	Modelo	JKM 340PP-72	Pnom	340 Wp
Conjunto FV	Núm. de módulos	29412	Pnom total	**10000 kWp**
Inversor	Modelo	Sunny Central 2200	Pnom	2200 kW ac
Paquete de inversores	Núm. de unidades	4.0	Pnom total	**8800 kW ac**
Necesidades del usuario	Carga ilimitada (red)			

Resultados principales de la simulación				
Producción del sistema	**Energía producida**	**13336 MWh/año**	Produc. específica	1334 kWh/kWp/año
	Índice de rendimiento (PR)	72.13 %		
Inversión	Total incl. impuestos	4358034.86 EUR	Específico	0.44 EUR/Wp
Costo anual	Anualidades (Préstamo 3.00%, 20 años)	292928.40 EUR/año	Costo de explotación	200001.60 EUR/año
Costo de energía		**0.03 EUR/kWh**	Payback period	**9.7 años**

Producciones normalizadas (por kWp instalado): Potencia nominal 10000 kWp



Índice de rendimiento (PR)



Nueva variante de simulación

Balances y resultados principales

	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray MWh	E_Grid MWh	PR
Enero	64.3	23.39	7.83	118.6	112.5	910	893	0.753
Febrero	82.0	35.50	9.05	124.5	117.9	958	941	0.756
Marzo	130.3	46.60	12.05	164.1	155.2	1222	1200	0.732
Abril	162.7	65.20	14.35	173.8	163.5	1285	1262	0.727
Mayo	195.5	82.40	18.12	179.8	168.4	1310	1287	0.716
Junio	201.2	82.62	22.22	175.6	164.3	1257	1236	0.703
Julio	218.6	76.80	24.47	195.2	183.0	1377	1353	0.693
Agosto	184.0	72.29	24.54	182.8	171.8	1290	1268	0.694
Septiembre	140.2	54.40	20.80	165.7	156.4	1189	1169	0.706
Octubre	103.7	39.40	17.53	148.1	140.4	1086	1067	0.720
Noviembre	67.6	28.80	11.92	113.4	107.5	858	842	0.743
Diciembre	55.6	23.10	8.42	107.5	102.0	832	817	0.760
Año	1605.7	630.50	15.98	1848.9	1743.1	13574	13336	0.721

Leyendas:
- GlobHor: Irradiación global horizontal
- DiffHor: Irradiación difusa horizontal
- T_Amb: Temperatura Ambiente
- GlobInc: Global incidente plano receptor
- GlobEff: Global efectivo, corr. para IAM y sombreados
- EArray: Energía efectiva en la salida del conjunto
- E_Grid: Energía inyectada en la red
- PR: Índice de rendimiento

Fig. 11-8. 10MW Grid-Connected PV System (Polycrystalline). Main results.

Sistema Conectado a la Red: Evaluación económica

Proyecto : **10MW Grid-Connected PV System (polycrystalline)**

Variante de simulación : **Nueva variante de simulación**

Simulación para la 25.° año de funcionamiento

Parámetros principales del sistema	Tipo de sistema	**No hay escenario 3D, no hay sombreados**		
Orientación Campos FV	inclinación	41°	acimut	0°
Módulos FV	Modelo	JKM 340PP-72	Pnom	340 Wp
Conjunto FV	Núm. de módulos	29412	Pnom total	**10000 kWp**
Inversor	Modelo	Sunny Central 2200	Pnom	2200 kW ac
Paquete de inversores	Núm. de unidades	4.0	Pnom total	**8800 kW ac**
Necesidades del usuario	Carga ilimitada (red)			

Inversión

Direct costs			
Módulos FV	7353 unidades	266.29 EUR / unidad	1958015.66 EUR
Inversores			500004.00 EUR
Installation			1300010.40 EUR
Other (wiring, structure, racking, etc.)			600004.80 EUR
		Inversión neta (CAPEX)	**4358034.86 EUR**

Operating costs

OPEX		200001.60 EUR / año
	Total (OPEX)	**200001.60 EUR / año**
	Operating costs (OPEX) incl. Inflation (1.00%)	**223789.51 EUR / año**

Resumen del sistema

Inversión neta		**4358034.86 EUR**
Own funds		0.00 EUR
Préstamo (20 años) Tasa 3.00 % / año	Anualidades 292928.40 EUR / año	4358034.86 EUR
Costo total anual (inc. inflation 1.00 % / año)		**458132.23 EUR / año**
Energía producida		**13336 MWh / año**
Costo de la energía producida		**0.03 EUR / kWh**
(sum of costs over lifetime / total production over lifetime)		

Fig. 11-9. 10MW Grid-Connected PV System (Polycrystalline). Economical results.

Both simulations had not considered any shadows between the panels to provide energy production results, even so the energy production results are correct the total area occupied by the system are not. Because of that an additional calculation of the area occupied by the system has to be done.

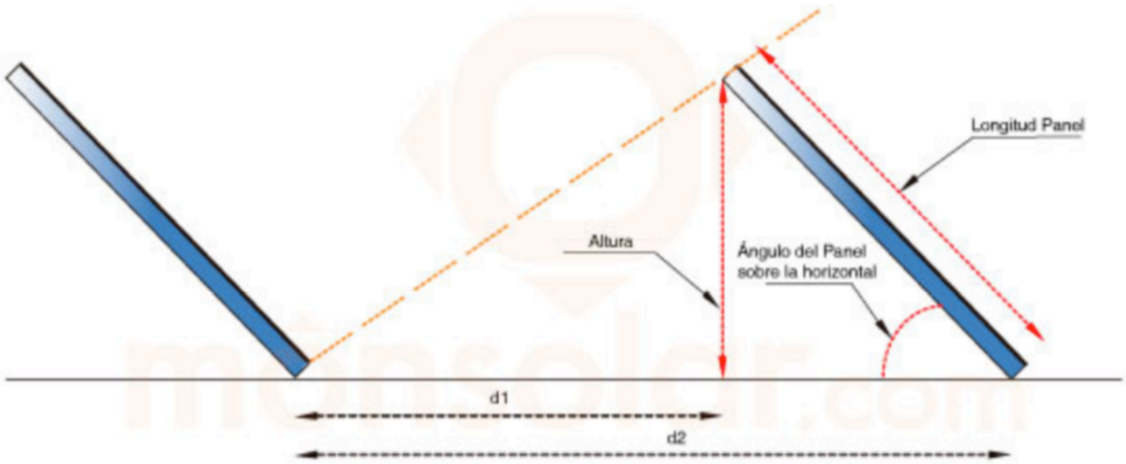


Fig. 11-10. PV panels shadowing scheme

To calculate the distance between the panels the following formula has been used:

$$d_1 = \frac{h}{\tan{(61 - lattitude)}} \qquad \text{(Eq.30)}$$

$$d_1 = \frac{1{,}956}{\tan{(61 - 41)}} = 3{,}525m$$

This formula calculates the required distance between strings to guarantee a minimum of 4 four hours of sun during the midday of the winter solstice.

To distance d_1 is necessary to add the distance occupied by the panel:

$$d_2 = d_1 + logitude\ of\ the\ panel \cdot \cos{(41)} \qquad \text{(Eq.31)}$$

$$d_2 = 3{,}525 + 1{,}965 \cdot \cos(41) = 4{,}73m$$

With these results and considering that each PV field will have 387 strings, the length of each panel (0,992m) and that 19 panels are going to be installed per string. The resulting required area for each PV field of both systems will be of:

$$Total\ Area\ = 387 \cdot 4{,}73 \cdot 19 \cdot 0{,}992 = 34.501{,}45m^2$$

That provides a final total area for each grid-connected PV-system of 138.005,81m^2 that more than double the area estimated by the software.

12. Economic Analysis of the Systems

Table 12-1 summarizes the results obtained after simulating the monocrystalline and polycrystalline grid-connected PV systems.

	Monocrystalline	**Polycrystalline**
Number of strings	1548	1548
Number of PV modules per string	19	19
Total number of PV modules	29412	29412
Number of inverters	4	4
Area required (m2)	57070	57070
Yearly energy production (MWh/year)	13348	13336
Net investment (CAPEX)	€ 4.600.036,80	€ 4.358.034,86
Operating costs (per year)	€ 200.001,60	€ 200.001,60

Table 12-1. Simulation main results summary

The results of the previous table, show that the main differences between installing one technology or the other is the energy production and the capital expenditures. Levelized Cost of Energy (LCOE) is an adequate tool to compare the competitiveness of the different technologies.

The Levelized Cost of Energy (LCOE) represent the average revenue per unit of electricity produced that would be required to recover the costs associated to the construction and operation of a generation plant. A high LCOE is associated with a high cost production and as a consequence to less returns.

$$LCOE = \frac{Lifetime\ Cost\ of\ the\ System}{Lifetime\ Energy\ Production\ of\ the\ System} \qquad \text{(Eq.32)}$$

Monocrystalline grid connected PV system:

$$LCOE = \frac{4.600.036{,}80 + (200.001{,}60 \cdot 25)}{13.348.000 \cdot 25} = 0{,}0287\ EUR/kWh$$

Polycrystalline grid connected PV system:

$$LCOE = \frac{4.358.034{,}86 + (200.001{,}60 \cdot 25)}{13.336.000 \cdot 25} = 0{,}0281\ EUR/kWh$$

The lower LCOE of the polycrystalline grid connected PV system shows that energy production cost of this technology is lower than the production cost of the monocrystalline.

Table *12-2* and Table *12-3* show the detailed economical analysis of the different systems. These results have been obtained from the simulation and consider an interest rate and an inflation of a 3% and 1% respectively.

Year	Sold energy	Loan principal	Interest (3%)	OPEX	Profit	Cumulative profit	% amortized
1	766	171	138	200	257	257	9.3%
2	766	176	133	202	255	512	18.7%
3	766	182	128	204	253	765	28.1%
4	766	187	122	206	251	1016	37.7%
5	766	193	117	208	249	1265	47.3%
6	766	198	111	210	247	1511	56.9%
7	766	204	105	212	245	1756	66.7%
8	766	211	99	214	243	1999	76.5%
9	766	217	92	217	240	2239	86.5%
10	766	223	86	219	238	2477	96.5%
11	766	230	79	221	236	2713	106.6%
12	766	237	72	223	234	2947	116.9%
13	766	244	65	225	232	3179	127.2%
14	766	251	58	228	229	3408	137.7%
15	766	259	50	230	227	3635	148.2%
16	766	267	42	232	225	3860	158.9%
17	766	275	34	235	222	4082	169.7%
18	766	283	26	237	220	4302	180.7%
19	766	291	18	239	218	4520	191.7%
20	766	300	9	242	215	4736	202.9%
21	383	0	0	244	139	4875	206.0%
22	383	0	0	246	137	5011	208.9%
23	383	0	0	249	134	5145	211.9%
24	383	0	0	251	132	5277	214.7%
25	383	0	0	254	129	5406	217.5%
Total	**17239**	**4600**	**1584**	**5649**	**5406**	**5406**	**217.5%**

Table 12-2. Detailed economic results for the monocrystalline PV system

Year	Sold energy	Loan principal	Interest (3%)	OPEX	Profit	Cumulative profit	% amortized
1	765.5	162.2	130.7	200.0	272.6	272.6	10.0%
2	765.5	167.1	125.9	202.0	270.6	543.2	20.0%
3	765.5	172.1	120.9	204.0	268.6	811.7	30.1%
4	765.5	177.2	115.7	206.1	266.5	1078.2	40.3%
5	765.5	182.5	110.4	208.1	264.5	1342.7	50.6%
6	765.5	188.0	104.9	210.2	262.4	1605.1	60.9%
7	765.5	193.7	99.3	212.3	260.3	1865.3	71.3%
8	765.5	199.5	93.5	214.4	258.1	2123.5	81.8%
9	765.5	205.5	87.5	216.6	256.0	2379.5	92.4%
10	765.5	211.6	81.3	218.7	253.8	2633.3	103.1%
11	765.5	218.0	75.0	220.9	251.7	2885.0	113.9%
12	765.5	224.5	68.4	223.1	249.4	3134.4	124.7%
13	765.5	231.2	61.7	225.4	247.2	3381.6	135.7%
14	765.5	238.2	54.8	227.6	245.0	3626.6	146.8%
15	765.5	245.3	47.6	229.9	242.7	3869.3	158.0%
16	765.5	252.7	40.2	232.2	240.4	4109.7	169.3%
17	765.5	260.3	32.7	234.5	238.1	4347.7	180.8%
18	765.5	268.1	24.9	236.9	235.7	4583.4	192.3%
19	765.5	276.1	16.8	239.2	233.3	4816.8	204.0%
20	765.5	284.4	8.5	241.6	231.0	5047.7	215.8%
21	382.8	0.0	0.0	244.0	138.7	5186.4	219.0%
22	382.8	0.0	0.0	246.5	136.3	5322.7	222.1%
23	382.8	0.0	0.0	248.9	133.8	5456.5	225.2%
24	382.8	0.0	0.0	251.4	131.3	5587.9	228.2%
25	382.8	0.0	0.0	253.9	128.8	5716.7	231.2%
Total	**17223.9**	**4358.0**	**1500.5**	**5648.7**	**5716.7**	**5716.7**	**231.2%**

Table 12-3. Detailed economic results for the polycrystalline PV system.

As can be seen in Table 12-2 and Table 12-3 the polycrystalline grid-connected PV system will be amortized in 9 years instead of 10 years required for the monocrystalline grid-connected PV system amortization.

Also, can be seen in the tables above that the wear of the panels produce a significant decrease in the electric energy sold during the last 5 years of operation.

13. Environmental impacts

Photovoltaic energy production is characterized by produce energy from an inexhaustible source. This characteristic allows an environmental respectful energy production.

PV plants present the following advantages respect other energy sources:

- Reduction of the fossil fuels dependency in the electrical system.
- Avoid or reduce the emission of CO_2 and other contaminant gases.
- Low waste production during its operation.

However, some environmental impacts as land and water use and cells life cycle, are associated to the installation of a photovoltaic power plant.

Land use
Large scale PV plants uses big areas to be installed, which will have an important visual impact and can raise concerns about degradation of the land and habitat loss. Even so, the impact associated to non-renewable generation plant will be higher.

Water use
Solar PV systems do not use water for energy generation but as in all fabrication process water is used. In addition, water will be required for cleaning the dust of the PV panels. But this water remains uncontaminated and can return to the water cycle without any treatment.

Hazardous materials
PV cell manufacturing requires the use of some hazardous materials mostly used to purify and clean the semiconductor surface. These compounds includes hydrochloric acid, sulfuric acid, nitric acid, hydrogen fluoride, 1,1,1,-trichloroethane, and acetone. The type and quantity required of these chemicals depend on the type of the cell and the size of the silicon wafer. Because of the hazardous of these compounds PV manufacturers must ensure that manufacturing waste products are treated according to the legislation [38].

Global Warming Emissions
According to the web electricity map [37], in Spain 231g of CO_2 are emitted for each kWh produced. Considering this number with the installation of the PV plant object of study is possible to avoid the emission of at least 3.080T of CO_2 each year. However, during the whole lifecycle of a photovoltaic system there are some emissions associated, but of course these emissions are far less than the life cycle emission rates of conventional sources.

14. Thesis budget

The cost of doing this thesis includes the working hours invested in researching and writing the thesis, as well as the cost of the student version of the software used to make the simulations. The table below summarizes the final master thesis budget.

Concept	**EUR/h**	**Hours**	**Cost (EUR)**
Selection of the project subject	25	100	2.500,00 €
Research	25	400	10.000,00€
Writing	25	350	8.750,00€
Total cost of hours invested		850	21.250,00€
Software license (one year)			21,89€
Total cost			**21.271,89€**

Table 14-1. Thesis budget

Conclusion

This thesis has presented and compared the installation of the most used technologies for large scale PV plants, monocrystalline and polycrystalline solar cells, in a 10MW grid-connected PV plant located in Cabrera de Mar, Spain. The selection of the components has been done in order to guarantee that the comparison between them is done by using the most similar performance between both technologies. Initially the first sizing of the different systems shows differences between the area and number of modules required, being both items bigger for the polycrystalline grid connected PV system due to the better performance of monocrystalline cells with temperature.

The second sizing done with PV SYST and the simulation obtained from it, provide the investment cost, the operation and maintenance cost and the yearly energy production of the two evaluated systems. The results show that for both systems the number of modules required are the same and in consequence the area. Nevertheless, the results of the simulation also show a higher energy production and a higher investment cost for the monocrystalline PV system. However, to make a more detailed comparison an economic analysis had been done in order to obtain the payback, amortization and the LCOE of both technologies. The payback time, amortization and the LCOE obtained in this analysis show that the polycrystalline grid connected PV system is the better option to be installed in the power plant simulated in Cabrera de Mar. That means that the investment cost of the polycrystalline system is returned in less time than the investment cost of monocrystalline, that more benefits are going to be obtained during the operation period of the plant and the cost per kWh produced in the polycrystalline system is smaller than the cost of the monocrystalline.

The results of the simulation for the preferable PV system show an energy production of 13.336 MWh. With the implementation of this system 3.080T of CO_2 that will be emitted to produce the same amount of energy by the Spanish electricity mix will be avoided.

In this project assumptions like the costs of installation, electrical components as wiring and structure or the fixed selling price has been done. For further studies a more detailed information and design will be needed. It should include in the economic part a request to the suppliers of the real selling prices of the components considering the quantity required and in the technical part a more detailed study of the electrical connections and protections that were not considered in this project.

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Appendix I – Monocrystalline panel data sheet

www.jinkosolar.com

JinKO Solar
Building Your Trust in Solar

Eagle 72M
330-350 Watt
MONO CRYSTALLINE MODULE

Positive power tolerance of 0~+3%

ISO9001:2008、ISO14001:2004、OHSAS18001 certified factory.
IEC61215、IEC61730 certified products.

(5BB)

PV CYCLE · CE · POSITIVE QUALITY · CLEAN ENERGY COUNCIL MEMBER

KEY FEATURES

5 Busbar Solar Cell:
5 busbar solar cell adopts new technology to improve the efficiency of modules , offers a better aesthetic appearance, making it perfect for rooftop installation.

PID RESISTANT:
Limited power degradation of Eagle module caused by PID effect is guaranteed under strict testing condition (85 C /85%RH,96hours)for mass production.

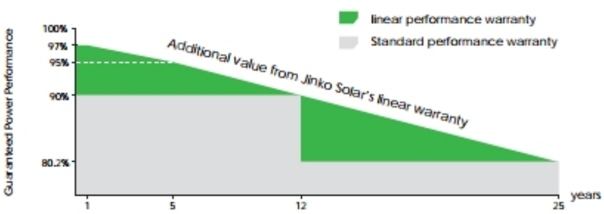
Low-light Performance:
Advanced glass and solar cell surface texturing allow for excellent performance in low-light environments.

Severe Weather Resilience:
Certified to withstand: wind load (2400 Pascal) and snow load (5400 Pascal).

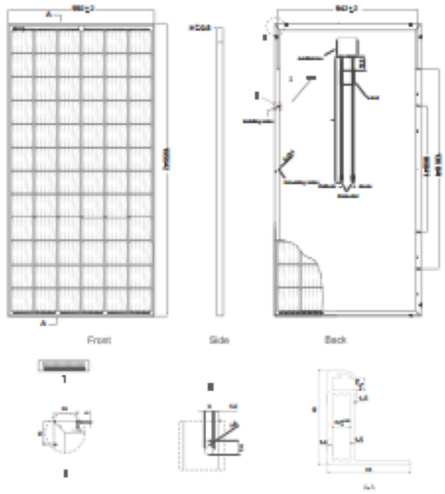
Durability against extreme environmental conditions:
High salt mist and ammonia resistance certified by TUV NORD.

LINEAR PERFORMANCE WARRANTY

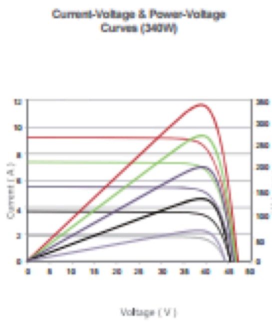
10 Year Product Warranty • 25 Year Linear Power Warranty

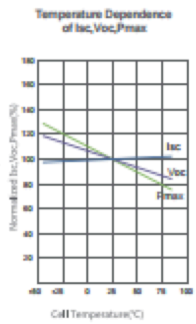


Engineering Drawings



Electrical Performance & Temperature Dependence





Mechanical Characteristics

Cell Type	Mono-crystalline 156×156mm (6 inch)
No.of cells	72 (6×12)
Dimensions	1956×992×40mm (77.01×39.05×1.57 inch)
Weight	22.5 kg (49.6 lbs)
Front Glass	3.2mm, Anti-Reflection Coating, High Transmission, Low Iron, Tempered Glass
Frame	Anodized Aluminium Alloy
Junction Box	IP67 Rated
Output Cables	TÜV 1×4.0mm², Length:900mm or Customized Length

Packaging Configuration

(Two pallets = One stack)

26pcs/pallet , 52pcs/stack, 624 pcs/40'HQ Container

SPECIFICATIONS

Module Type	JKM330M-72		JKM335M-72		JKM340M-72		JKM345M-72		JKM350M-72	
	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT
Maximum Power (Pmax)	330Wp	246Wp	335Wp	250Wp	340Wp	254Wp	345Wp	258Wp	350Wp	262Wp
Maximum Power Voltage (Vmp)	38.2V	36.4V	38.4V	36.6V	38.7V	36.8V	38.9V	37.0V	39.1V	37.2V
Maximum Power Current (Imp)	8.64A	6.75A	8.72A	6.82A	8.79A	6.89A	8.87A	6.98A	8.94A	7.05A
Open-circuit Voltage (Voc)	46.7V	44.8V	46.9V	45.2V	47.1V	45.5V	47.3V	45.8V	47.5V	46.0V
Short-circuit Current (Isc)	9.11A	7.24A	9.18A	7.29A	9.24A	7.33A	9.31A	7.38A	9.38A	7.46A
Module Efficiency STC (%)	17.01%		17.26%		17.52%		17.78%		18.04%	
Operating Temperature(°C)	-40°C~+85°C									
Maximum system voltage	1000VDC (IEC)									
Maximum series fuse rating	20A									
Power tolerance	0~+3%									
Temperature coefficients of Pmax	-0.40%/°C									
Temperature coefficients of Voc	-0.29%/°C									
Temperature coefficients of Isc	0.048%/°C									
Nominal operating cell temperature (NOCT)	45±2°C									

* STC: Irradiance 1000W/m² Cell Temperature 25°C AM=1.5

NOCT: Irradiance 800W/m² Ambient Temperature 20°C AM=1.5 Wind Speed 1m/s

* Power measurement tolerance: ± 3%

The company reserves the final right for explanation on any of the information presented hereby. EN-JKM-350M-72_1.0_rev2017

Appendix II – Polycrystalline panel data sheet

www.jinkosolar.com

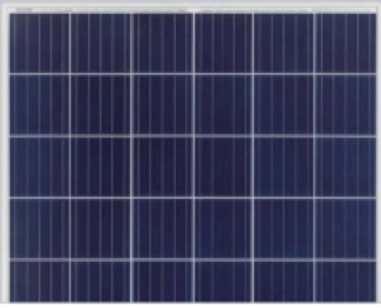
JinKO Solar
Building Your Trust in Solar

Eagle 72P
320-340 Watt
POLY CRYSTALLINE MODULE

Positive power tolerance of 0~+3%

ISO9001:2008、ISO14001:2004、OHSAS18001 certified factory.
IEC61215、IEC61730 certified products.

(5BB)



KEY FEATURES

5 Busbar Solar Cell:
5 busbar solar cell adopts new technology to improve the efficiency of modules , offers a better aesthetic appearance, making it perfect for rooftop installation.

High Power Output:
Polycrystalline 72-cell module achieves a power output up to 340Wp.

PID RESISTANT:
Eagle modules pass PID test, limited power degradation by PID test is guaranteed for mass production.

Low-light Performance:
Advanced glass and surface texturing allow for excellent performance in low-light environments.

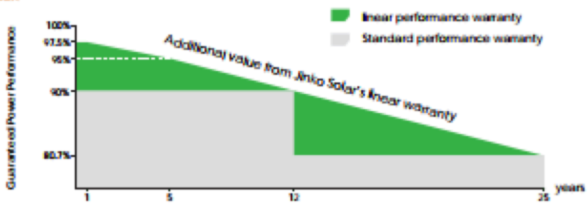
Severe Weather Resilience:
Certified to withstand: wind load (2400 Pascal) and snow load (5400 Pascal).

Durability against extreme environmental conditions:
High salt mist and ammonia resistance certified by TUV NORD.

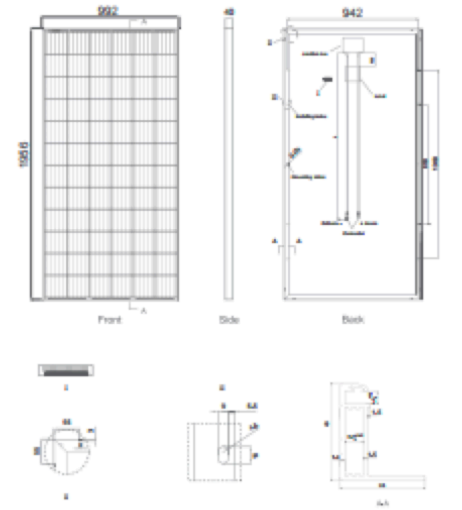
Temperature Coefficient:
Improved temperature coefficient decreases power loss during high temperatures.

LINEAR PERFORMANCE WARRANTY

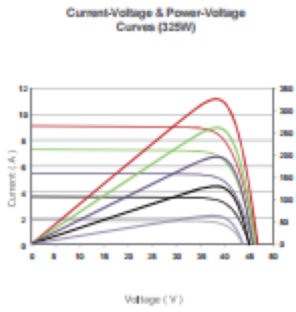
10 Year Product Warranty • 25 Year Linear Power Warranty

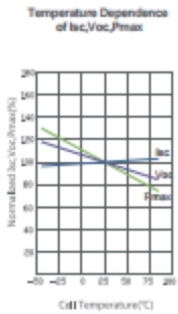


Engineering Drawings



Electrical Performance & Temperature Dependence





Packaging Configuration

(Two pallets=One stack)

26pcs/pallet, 52pcs/stack, 624 pcs/40'HQ Container

Mechanical Characteristics

Cell Type	Poly-crystalline 156×156mm (6 inch)
No.of cells	72 (6×12)
Dimensions	1956×992×40mm (77.01×39.05×1.57 inch)
Weight	22.5 kg (49.6 lbs.)
Front Glass	3.2mm, Anti-Reflection Coating, High Transmission, Low Iron, Tempered Glass
Frame	Anodized Aluminium Alloy
Junction Box	IP67 Rated
Output Cables	TÜV 1×4.0mm², Length: 1200mm or Customized Length

SPECIFICATIONS

Module Type	JKM320PP-72		JKM325PP-72		JKM330PP-72		JKM335PP-72		JKM340PP-72	
	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT
Maximum Power (Pmax)	320Wp	237Wp	325Wp	241Wp	330Wp	245Wp	335Wp	249Wp	340Wp	253Wp
Maximum Power Voltage (Vmp)	37.4V	34.7V	37.6V	35.0V	37.8V	35.3V	38.0V	35.6V	38.2V	35.9V
Maximum Power Current (Imp)	8.56A	6.83A	8.66A	6.89A	8.74A	6.94A	8.82A	6.99A	8.91A	7.05A
Open-circuit Voltage (Voc)	46.4V	43.0V	46.7V	43.3V	46.9V	43.6V	47.2V	43.8V	47.5V	44.0V
Short-circuit Current (Isc)	9.05A	7.35A	9.10A	7.40A	9.14A	7.45A	9.18A	7.52A	9.22A	7.98A
Module Efficiency STC (%)	16.49%		16.75%		17.01%		17.26%		17.52%	
Operating Temperature(℃)	-40℃~+85℃									
Maximum system voltage	1000VDC (IEC)									
Maximum series fuse rating	20A									
Power tolerance	0~+3%									
Temperature coefficients of Pmax	-0.40%/℃									
Temperature coefficients of Voc	-0.31%/℃									
Temperature coefficients of Isc	0.06%/℃									
Nominal operating cell temperature (NOCT)	45±2℃									

STC: Irradiance 1000W/m² Cell Temperature 25°C AM=1.5

NOCT: Irradiance 800W/m² Ambient Temperature 20°C AM=1.5 Wind Speed 1m/s

* Power measurement tolerance: ± 3%

The company reserves the final right for explanation on any of the information presented hereby. EN-JKM-340PP-72_rev2017

Appendix III. Inverter data sheet

SUNNY CENTRAL 2200

Technical Data	SC 2200
Input (DC)	
MPP voltage range V_{DC}	570–1000 V
Max. input voltage $V_{DC, max}$	1,000 V (1,100 IEC)
Max. input current $I_{DC, max}$ (at 25 °C / at 50 °C)	4,110 A / 3,960 A
Number of DC inputs	24
Max. number of DC cables per DC input (for each polarity)	2 x 800 kcmil, 2 x 400 mm²
Integrated zone monitoring (±0.5% shunt resistors)	○
Available DC fuse sizes (per input)	200 A, 250 A, 315 A, 350 A, 400 A, 450 A, 630 A
Output (AC)	
Nominal AC power at cos ϕ =1 (at 25 °C / at 40 °C / at 50 °C)	2,200 kVA / 2,080 kVA / 2,000 kVA
Nominal AC power at cos ϕ =0.9 (at 25 °C / at 40 °C / at 50 °C)	1,980 kW / 1,872 kW / 1,800 kW
Max. output current $I_{AC, max}$	3,300 A
Nominal AC current $I_{AC, nom}$	3,000 A
Max. total harmonic distortion	< 3% at nominal power
Nominal AC voltage / nominal AC voltage range	385 V / 347–424 V
AC power frequency	50 Hz, 60 Hz
Power factor at rated power / displacement power factor adjustable	1 / 0.8 overexcited to 0.8 underexcited
Efficiency [1, 2]	
Max. efficiency / European efficiency / CEC efficiency	98.6% / 98.3% / 98.0%
Protective Devices	
Input-side disconnection point	DC load-break switch
Output-side disconnection point	AC circuit breaker
DC overvoltage protection	Surge arrester, type II
Ground-fault monitoring / remote ground-fault monitoring	○ / ○
Insulation monitoring	○
Degree of protection (as per IEC 60529)	IP54
Degree of protection (as per NEMA)	3R
General Data	
Dimensions (W / H / D)	2,780 / 2,318 / 1,588 mm (108.7 / 90.5 / 65.7 inch)
Weight	< 4,000 kg / < 8,819 lb
Max. self-consumption (operation)[3] / self-consumption (standby)	< 8,100 W / < 300 W
Internal auxiliary power supply	Integrated 8.4 kVA transformer
Operating temperature range	-25 ... 60 °C / -13 ... 140 °F
Extended operating temperature range	○ (-40 ... 60 °C / -40 ... 140 °F)
Temperature range (standby)	-40 ... 60 °C / -40 ... 140 °F
Temperature range (storage)	-40 ... 70 °C / -40 ... 158 °F
Max. permissible value for relative humidity (condensation)	0 ... 100%
Maximum operating altitude above MSL 2,000 m / 4,000 m	● / ○ (with power reduction)
Fresh air consumption	6,500 m³/h
Features	
DC connection	Terminal lug on each input or one busbar (without fuse)
AC connection	With busbar system (three busbars, one per line conductor)
Communication	Ethernet, Ethernet/IP, Modbus Master, Modbus Slave
Communication with SMA string monitor	Ethernet (OF), Modbus
Enclosure / roof color	RAL 9016 / RAL 7004
Display	HMI touchscreen (10.1")
Supply transformer for external loads	○ (2.5 kVA)
Certificates and approvals	BDEW, EMC FCC Part 15 Class A, UL 1741, UL 1998, UL 840 Category IV, IEEE 1547, CE
● Standard features ○ Optional	
Type designation	SC-2200-10

1) Preliminary values
2) Efficiency measured without internal power supply
3) Self-consumption at rated operation

Appendix IV. Transformer data sheet

MV POWER STATION
2200SC / 2500SC-EV / 2750SC-EV

Technical data	MV Power Station 2200SC
Input (DC)	
Max. DC input voltage	1100 V
MPP voltage range (at 25 °C / at 50 °C)	570 V to 950 V / 850 V
Max. input current (at 25 °C / at 50 °C)	3960 A / 3600 A
Number of DC inputs	24
Integrated zone monitoring	○
Available DC fuse sizes (per input)	200 A, 250 A, 315 A, 350 A, 400 A, 450 A, 500 A
Output (AC) on the medium-voltage side	
AC- power at cos φ = 1 (at 25 °C / at 40 °C / at 50 °C / at 55 °C)[1]	2200 kVA / 2080 kVA / 2000 kVA / 0 kVA
Typical AC voltages	10 kV to 33 kV
AC power frequency	50 Hz / 60 Hz
Transformer vector group Dy11 / YNd11	● / ○
Transformer cooling method (ONAN / KNAN)[2]	● / ○
Max. output current at 20 kV	64 A
Transformer no-load losses[3]	1.595 kW
Transformer short-circuit losses[3]	19.8 kW
Max. total harmonic distortion	< 3%
Reactive power feed-in	up to 60% of AC power
Power factor at rated power / displacement power factor adjustable	1 / 0.8 overexcited to 0.8 underexcited
Inverter efficiency	
Max. efficiency	98.6%
European efficiency	98.4%
CEC weighted efficiency[4]	98.0%
Protective devices	
Input-side disconnection point	DC load-break switch
Output-side disconnection point	AC circuit breaker
DC overvoltage protection	Type II surge arrester
DC ground-fault monitoring / remote ground-fault monitoring	○ / ○
DC insulation monitoring	○
Galvanic isolation	●
Arc fault resistance control room (according to IEC 62271-202)	IAC A 20 kA 1 s
General data	
Dimensions of the 20-foot ISO container (W / H / D)[5]	6.058 m / 2.591 m / 2.438 m
Weight	< 16 t
Operating temperature range −25 °C to +40 °C / +55 °C	● / ○
Self-consumption (max. / partial load / average)[1]	< 8100 W / < 1800 W / < 2000 W
Self-consumption (stand-by)[1]	< 300 W
Internal auxiliary power supply for inverter self-consumption	8.4 kVA transformer
Degree of protection according to IEC 60529	Control room IP23D, inverter electronics IP65
Degree of protection according to IEC 60721-3-4 (4C1, 4S2 / 4C2, 4S2)	● / ○
Application / use in chemically active environment	In unprotected outdoor environments / ○
Maximum permissible value for relative humidity	15% to 95%
Max. operating altitude above mean sea level 1000 m / 2000 m	● / ○ (earlier temperature-dependent de-rating)
Fresh air consumption (inverter)	6500 m³/h
Features	
DC connection	Terminal lug
AC connection, MV side	Outer-cone angle plug
Display	○ HMI touch display (10.1")
Communication	Ethernet, Modbus
Station enclosure color	RAL 7004
Transformer for external loads 10 kVA / 20 kVA / 30 kVA	○
Medium-voltage switchgear, three feeders	○
Oil containment	○
Standards (for other standards see the inverter datasheet)	CSC certificate, EN 50588-1, IEC 62271-202, IEC 62271-200, IEC 60076
● Standard features ○ Optional features — Not available	
Type designation	MVPS 2200SC-10

ETSEIB

ETSEIB